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On Optimum Multiple-Alternative Detection of Signals in Noise*

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Summary—The problem of the optimum detection of signals in ise, when a possible signal can arise from more than one class of gnal types, is considered from the point of view of decision theory. ecifically, optimization here consists of minimizing the average sk for preassigned costs appropriate to the possible correct and correct decisions, when only a single signal, of class k, may occur it of $N + 1$ *mutually exclusive* signal classes. The analysis is a neralization of the authors' earlier work[1] on binary, or single ternative detection systems. The present treatment outlines the timization procedure for additive signals and noise, indicates the neral structure of the detector, and gives expressions for the obabilities of error and minimum average (or Bayes) risk. Some plicit results for normal statistics are included, and an example— herent detection of similar signals, differing only in amplitude— ustrates the general approach.

Introduction

CONSIDERABLE attention has been given recently to optimum detection systems for determining the presence or absence of a signal in noise[1,1a-3], when nly a single alternative is involved; i.e., when two decisions nly are made: "yes," a signal (as well as noise) is present, "no," only noise occurs. As in these simple binary ases, the methods of decision theory[1,1a,4] are also particurly well-suited to a systematic treatment of multiple ternative situations involving the possible presence of ore than one signal, or of a signal from more than one pe or class of signals, during a typical observation terval $(0, T)$.

Accordingly, the purpose of this paper is to extend the nary theory to include those multiple alternative situaons where a single signal only can appear (with noise) a any one observation, but the signal itself may be lected from a large number of different types or classes, where the distinguishing features of each class are not shared by any other. For example, waveform may be used to distinguish between signal classes: one may consist of an ensemble of sinewaves; another, of square waves; a third, of pulses, etc. Or amplitude may be used: one class may be composed of sinusoids whose amplitudes fall between a and $2a$; a second, of sinewaves with amplitudes in the range $(2a, 3a)$ and so on. Our problem is thus to decide, in some optimum fashion, which of the possible signals is present, when the true signal in each instance is corrupted by noise.

To do this, we employ here the notion of *risk*,[5] which associates certain costs with each possible decision, and uses the expected cost (or average risk) to evaluate system performance. Optimum detection, from this point of view, is then defined as that process which minimizes the average risk, and this minimum average, in turn, is called the *Bayes risk*[1]. Our procedure is first to construct the average risk function, and next to minimize it by suitable choice of the decision operation. The result reveals the explicit structure of the optimum detector itself, which, as in the single-alternative cases, is determined by the *a priori* noise and signal statistics, signal structure, and the preassigned costs.

The Average Risk

We begin with the *average risk* $R(\sigma, \delta)$, which is defined as[1]

$$R(\sigma,\ \delta) = \int_\Gamma d\mathbf{V} \int_\Omega d\mathbf{S} \int_\Delta d\boldsymbol{\gamma}\, C(\mathbf{S}, \boldsymbol{\gamma})F(\mathbf{V} \mid \mathbf{S})\sigma(\mathbf{S})\,\delta(\boldsymbol{\gamma} \mid \mathbf{V}). \tag{1}$$

Here $\sigma(\mathbf{S})$ is the *a priori* distribution of all possible signals $\mathbf{S}$, divided into $N + 1$ distinct classes. Writing

$$\left.\begin{aligned} \delta^{(k)}(\mathbf{S}) &= 1, &&\mathbf{S} \text{ belongs to class } k \\ &= 0, &&\text{otherwise} \end{aligned}\right\}, \tag{2}$$

we may express the distribution $\sigma(\mathbf{S})$ as

$$\sigma(\mathbf{S}) = \sum_{k=0}^{N} p_k \delta^{(k)}(\mathbf{S}) w_k(\mathbf{S}), \qquad \sum_0^N p_k = 1, \tag{3}$$

where p_k are the *a priori* probabilities that a signal from a class $k(=0, 1, \cdots, N)$ be present on any one observation, and the w_k are the probability (densities) governing the signals that fall within the class or type k. Here $k = 0$ represents the class of null signals, or noise alone. In the following, the superscript notation refers to the type of

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[5] For a detailed discussion of the method in communications problems, see sections 1 and 2 of reference 1.

signal, or hypothesis class, while subscripts refer to a particular signal, or components of that signal, within a class. Thus $\mathbf{S}_j^{(k)} = [S_{j1}^{(k)}, \cdots S_{jn}^{(k)}]$ denotes the jth signal in the kth class with its n components, each of which represents a value of the signal at a certain time, *i.e.*, $S_{jl}^{(k)} = S_j^{(k)}(t_l)$, etc., and these times are ordered, with $t_1 \leq t_2 \leq \cdots \leq t_n$. We shall use $\mathbf{S}^{(k)}$ to denote an unspecified signal of class k.

The received data are denoted by $\mathbf{V} = [V_1, \cdots, V_n]$, and the $N + 1$ hypothesis classes are taken to be mutually exclusive, so that the signals $\mathbf{S}_j^{(k)}$ are necessarily different from class to class (for different k's) as well as within each class (for different j's). The manner in which the various signals and the noise are combined determines the precise structure of the conditional probability $F(\mathbf{V} \mid \mathbf{S})$ for the received wave $\mathbf{V}$, when $\mathbf{S}$ is given. The quantities C and δ are, respectively, the *cost function* and the *decision rule* (expressed as a probability density of a decision $\gamma = (\gamma_0, \gamma_1, \cdots, \gamma_N)$, based on the data $\mathbf{V}$. Here the operation $\int_\Delta$ over decision space Δ in (1) is explicitly a sum over the $N + 1$ decision points $k = 0, 1, \cdots, N$. For example, γ_k is the decision that some signal of class k, as well as noise, is present. Making such a decision is equivalent to testing (and accepting) the hypothesis H_k against all other alternative hypothesis $H_j (j \neq k; j, k = 0, \cdots N)$. We require also that

$$\sum_{k=0}^{N} \delta(\gamma_k \mid \mathbf{V}) = 1, \tag{4}$$

which is simply a statement of the fact that a definite decision of some kind must be made.

Constant costs are next assigned to the possible outcomes, according to the usual procedure in risk theory[1]. We write

$C_j^{(k)}$ = cost associated with the decision that some signal of class j is present, when actually a signal (and noise) from class k occurs, $(j, k = 0, 1, \cdots N)$.

For "successful" or correct decisions we have then:

$$\left.\begin{array}{lll} C(\mathbf{S}^{(0)}; \gamma_0) = C_0^{(0)}: & \text{noise alone correctly detected} \\ C(\mathbf{S}^{(k)}; \gamma_k) = C_k^{(k)}: & \text{signal } \mathbf{S}^{(k)} \text{ correctly detected} \\ & (k = 1, \cdots, N). \end{array}\right\} \tag{5}$$

The costs preassigned to "failures," or incorrect decisions, are represented by

$$\left.\begin{array}{ll} C(\mathbf{S}^{(0)}; \gamma_j) = C_j^{(0)}: & \text{signal } \mathbf{S}^{(j)} \text{ incorrectly decided upon when only noise is present } (j \neq 0) \\ C(\mathbf{S}^{(k)}; \gamma_j) = C_j^{(k)}: & \text{signal } \mathbf{S}^{(j)} \text{ detected, when } \mathbf{S}^{(k)} \text{ is actually present } (j \neq k). \end{array}\right\} \tag{6}$$

Note that in assigning costs, no distinctions between different signals of the same class are made. From the definition of failure and success we require also that

$$C_k^{(k)} < C_j^{(k)} (j \neq k); \; C_0^{(0)} < C_j^{(0)} (j \neq 0); \; C_j^{(k)} \geq 0. \tag{7}$$

In what follows we assume that signals and noise are additive and independent: $\mathbf{V} = \mathbf{S}^{(k)} + \mathbf{N}$; $(k = 0, \cdots N)$, so that $F(\mathbf{V} \mid \mathbf{S})$ becomes $W_n(\mathbf{V} - \mathbf{S})$, where W_n is the nth order probability density of *noise alone*. Applying (2)-(7) to the average risk, and writing $p_0 = q$, we readily obtain for (1) on integrating over decision space Δ,

$$R_N(\sigma, \delta) = \int_\Gamma \left\{ \left[C_0^{(0)} \delta(\gamma_0 \mid \mathbf{V}) + \sum_{k=1}^{N} C_k^{(0)} \delta(\gamma_k \mid \mathbf{V}) \right] q W_n(\mathbf{V}) + \left[\sum_{k=1}^{N} p_k \left\{ C_k^{(k)} \delta(\gamma_k \mid \mathbf{V}) + \sum_{j=0}^{N}{}' C_j^{(k)} \delta(\gamma_j \mid \mathbf{V}) \right\} \langle W_n(\mathbf{V} - \mathbf{S}^{(k)}) \rangle_k \right] \right\} d\mathbf{V}, \tag{8}$$

subject to the conditions (4) and (7), where $\langle \ \ \rangle_k$ indicates the statistical average over $\mathbf{S}^{(k)}$, with respect to w_k, cf. (3), and the prime on the summation means that $(j \neq k)$. Note that where $N = 1$ (the binary case), (8) reduces with the help of (7) to the earlier expression (21, 22)[1] with obvious changes in notation, cf. (15) therein, etc.

Minimization of the Average Risk; The Optimum Detector

It is now convenient to rearrange (8), with the help of (4), by collecting coefficients of $\delta(\gamma_k \mid \mathbf{V})$. Introducing the quantities

$$\text{(i)} \left\{\begin{array}{l} \lambda_k^{(l)} \equiv C_k^{(l)} - C_0^{(l)}, \quad l \neq k, \quad (k, l = 1, \cdots N), \\ \text{with} \quad \lambda_k^{(0)} > 0, \quad k > 0; \quad \lambda_k^{(k)} < 0, \quad (k \neq 0), \\ \lambda_l^{(0)} \equiv C_l^{(0)} - C_0^{(0)}, \quad (l = 1, \cdots N). \\ \qquad \lambda_k^{(l)} \gtreqless 0 (k \neq l) \\ \lambda_k^{(k)} \equiv C_k^{(k)} - C_0^{(k)} \end{array}\right\} \tag{9}$$

$$\text{(ii)} \qquad \Lambda_k(\mathbf{V}) \equiv p_k \langle W_n(\mathbf{V} - \mathbf{S}^{(k)}) \rangle_k / q W_n(\mathbf{V}) \geq 0, \tag{10}$$

$$\text{(iii)} \qquad A_k(\mathbf{V}) \equiv \lambda_k^{(0)} + \sum_{l=1}^{N} \lambda_k^{(l)} \Lambda_l(\mathbf{V}), \tag{11}$$

we find after some algebra that the average risk (8) may be written

$$R_N(\sigma, \delta) = \mathcal{R}_0 + \mathcal{R}_N, \tag{12}$$

where $\mathcal{R}_0 = qC_0^{(0)} + \sum_1^N p_k C_0^{(k)}$ (> 0) is simply the expected cost of calling every signal (including noise), "noise," and

$$\mathcal{R}_N = \int_\Gamma \left[\sum_{k=1}^{N} \delta(\gamma_k \mid \mathbf{V}) A_k(\mathbf{V}) \right] q W_n(\mathbf{V}) \, d\mathbf{V}, \tag{13}$$

which is the part of the average risk that may be adjusted through choice of δ; $\mathcal{R}_0 \geq \mathcal{R}_N$, from the conditions (7). The quantities $\Lambda_k(\mathbf{V})$, $(k = 1, \cdots, N)$, are *generalized likelihood ratios,*[1,2] whose precise form determines the structure of our $(N + 1)$-ary detector. The process of detection itself is now specified by our choice of the δ's and the corresponding regions for the $\Lambda_k(\mathbf{V})$, (all $\mathbf{V}$), which are nonoverlapping for the mutually exclusive hypotheses considered here.

Since we are interested in *optimum* detection, our oblem now is to choose $\delta(\gamma_k \mid \mathbf{V})$, for given $\mathbf{V}$, in such a ay that the average risk $\mathcal{R}_N$ (and hence R_N) is minimized. asically, this is the problem of determining the bounries of the critical regions for Λ_k ($\mathbf{V}$), which from (11) d (13) we suspect will be set by a series of *linear* equaons in the various likelihood ratios.

The argument for minimization is easily given: since W_n ($\mathbf{V}$) ≥ 0 everywhere in Γ, the average risk (12, 13) is ast where for each value of $\mathbf{V}$ we choose δ appropriately minimize $\sum_1^N \delta_k A_k$, subject for the moment to the sumption that for this given $\mathbf{V}$ there exists an A_k ($\mathbf{V}$) hich is (algebraically) less than all other A_j ($\mathbf{V}$), ($j \neq k$). he procedure, thus, is to examine all A's for the given $\mathbf{V}$, lecting that one (A_k) which is algebraically least, *and en choosing* (for the same $\mathbf{V}$) $\delta(\gamma_k \mid \mathbf{V}) = 1$, $\delta(\gamma_j \mid \mathbf{V}) = 0$, $\neq k$, all j). Repeating for all $\mathbf{V}$ in Γ we obtain finally a t of conditions in the A_k's, for all ($k = 1, \cdots N$). Note om the form of (13), (the δ's appear linearly) and from e process of minimization itself, that δ is automatically nonrandomized decision rule (i.e., $\delta = 1$ or 0 only). nce the A_k ($\mathbf{V}$) possibly contain negative parts (9), we e that to minimize the average risk and make a decision (signal $\mathbf{S}^{(k)}$ present in noise) on the basis of received ta $\mathbf{V}$, the specific conditions on the A_k must be that the ta $\mathbf{V}$ satisfy the *inequalities*:

$$^{(0)} + \sum_{l=1}^{N} \Lambda_l(\mathbf{V})\lambda_k^{(l)} \leq \lambda_j^{(0)} + \sum_{l=1}^{N} \lambda_j^{(l)} \Lambda_l(\mathbf{V}),$$

$$\text{all } j \neq k, \qquad (j = 1 \cdots N) \tag{14}$$

$$^{(0)} + \sum_{l=1}^{N} \lambda_k^{(l)} \Lambda_l(\mathbf{V}) \leq 0,$$

ith $\quad \delta(\gamma_k \mid \mathbf{V}) = 1; \quad \delta(\gamma_j \mid \mathbf{V}) = 0.$

or each possible decision γ_k, ($k = 1 \cdots N$), this applies. he only remaining set of inequalities covers the case of oise alone ($k = 0$); we have here the conditions

$$\lambda_k^{(0)} + \sum_{l=1}^{N} \lambda_k^{(l)} \Lambda_l(\mathbf{V}) \geq 0, \qquad (k = 1, \cdots, N) \tag{15}$$

ith

$$\gamma_0 \mid \mathbf{V}) = 1; \quad \delta(\gamma_j \mid \mathbf{V}) = 0, \qquad (j = 1, \cdots, N).$$

If now we regard the Λ's as our independent variables, e can at once give a direct geometric interpretation of the utually exclusive sets of conditions (14), (15). Writing L_k) as the value of the quantity $\lambda_k^{(0)} + \sum_{l=1}^N \lambda_k^{(l)} \Lambda_l$ ($\mathbf{V}$) nd L_k for the hypersurface[6] $L_k = 0$, we observe that in onjunction with the hypersurfaces forming the boundaries the first "2^{N+1}-tant"[7], the *equalities* in the conditions 4) or (15) give the boundaries of a *closed* region within hich lie all values of Λ_k ($\mathbf{V}$) associated with the decision γ_k. Each closed region is distinct from every other, and the N planar hypersurfaces which form its boundaries are then from (14) and (15) specified by

$$\begin{cases} L_k = 0;\ L_k - L_j = 0;\ \text{all } j = 1, \cdots N;\ (j \neq k); & (16) \\ \qquad\qquad (\text{for each } \gamma_k,\ k = 1, \cdots N) & \\ L_k = 0;\ \text{all } k = 1, \cdots, N; \qquad (\text{for } \gamma_0). & (17) \end{cases}$$

Solving the N linear equations (14), (15), or (16, 17), one can show in straightforward fashion that the various (distinct) N planar hypersurfaces determining the boundaries of each region all intersect at a point $\mathbf{K} = (K_0^{(1)} \cdots K_0^{(N)})$, where now the K's represent a set of N *thresholds* Λ_k ($\mathbf{V}'$) $= K_0^{(k)}$, ($k = 1, \cdots N$), in which $\mathbf{V}'$ are all values of $\mathbf{V}$ satisfying this relation. These thresholds depend explicitly only on the preassigned costs, i.e. on the λ's of (14) etc., and the requirement (7) insures that the point $\mathbf{K}$ lies in the first 2^{N+1}-tant, i.e., all $K^{(k)} \geq 0$.

A simpler variant of (14), also of practical interest, arises where the problem becomes that of testing for the presence of one signal $\mathbf{S}^{(k)}$ in noise against (any one of the) other possible nonzero signals in *noise*; the case of noise alone is eliminated. Under these circumstances the costs $C_0^{(l)}$, $C_0^{(0)}$, $C_l^{(0)}$ drop out, and the λ's of (9) *et seq.*, are simply $\lambda_k^{(l)} = C_k^{(l)}$, ($k, l = 1, \cdots, N$) > 0. Consequently, the A_k ($\mathbf{V}$) can never be negative, and minimization of the average risk gives only the first set of inequalities in (14), with $\lambda_k^{(0)} = \lambda_j^{(0)} = 0$, so that we may write then for the decision γ_k, the modified conditions

$$\sum_{l=1}^{N} \Lambda_l(\mathbf{V}) C_k^{(l)} \leq \sum_{l=1}^{N} \Lambda_l(\mathbf{V}) C_j^{(l)},$$

$$(j \neq k;\ \text{all } j = 1, \cdots N), \tag{18}$$

repeated for each ($k = 1, \cdots, N$) in turn. The point $\mathbf{K} = 0$ now, and all decision regions (for the Λ's) have their apices at the origin. The bounding hyperplanes all intersect at $\mathbf{K} = 0$, and the equations of the boundaries of the kth region are simply

$$L_k - L_j = 0; \quad (\text{all } j = 1, \cdots N), \quad (j \neq k);$$

$$(\text{for each } \gamma_k,\ k = 1 \cdots N). \tag{19}$$

To summarize, then, we see that the optimum ($N + 1$)-ary (or N-ary above) detector consists of a computer which evaluates the Λ_k ($\mathbf{V}$) for a given set of data $\mathbf{V}$ over the observation period (0, T), computes the various A_k ($\mathbf{V}$) and then inserts the results into the inequalities (14), (15), or (18), finally making the decision $\gamma_{(k)}$ associated with the one set of inequalities that is satisfied.[8]

We illustrate the remarks of this section by:

(a) *Binary Detection*

The simplest and most familiar[1-3] case of (14), (15) arises when we have to distinguish $\mathbf{S}^{(1)} + \mathbf{N}$ versus $\mathbf{N}$

[6] For $N \geq 4$, $L_k = 0$ is a plane hypersurface (in $\Lambda_1, \cdots, \Lambda_N$-ace); for $N = 1, 2$, $L_k = 0$ represents a straight line in 2 dimensions f Λ_1, Λ_2-space), while for $N = 3$, $L_k = 0$ represents a plane surface Λ_1, Λ_2, Λ_3-space).

[7] For example, if $N = 1$ the first "2^2-tant" = first "quadrant"; $N = 2$, = first "octant," etc. Since likelihood ratios Λ_k can never negative, values of $\Lambda_k(\mathbf{V})$ must always lie in the first "2^{N+1}-tant."

[8] Of course, this is not a unique way of setting up an actual computing scheme; one might use, for example, an appropriate number of binary decisions with appropriate limits; but in any case, the operation must be equivalent to the above.

alone, so that $N = 1$. With the help of (9) in (14), (15) we easily find that we

$$\left.\begin{array}{lll} \text{decide } \gamma_0: & \mathbf{N}, & \text{if } \Lambda_1(\mathbf{V}) < \\ \text{decide } \gamma_1: & \mathbf{S}^{(1)} + \mathbf{N}, & \text{if } \Lambda_1(\mathbf{V}) > \end{array}\right\}$$

$$-\frac{\lambda_1^{(0)}}{\lambda_1^{(1)}} = \frac{C_1^{(0)} - C_0^{(0)}}{C_0^{(1)} - C_1^{(1)}} = \frac{C_\alpha - C_{1-\alpha}}{C_\beta - C_{1-\beta}} \equiv K_0^{(1)}, \tag{20}$$

with the threshold $K_0^{(1)}$ a function of the costs only. [C_α, $C_{1-\alpha}$, etc. are expressed in the earlier notation of references 1 and 2.]

The more general binary problem of distinguishing $\mathbf{S}^{(a)} + \mathbf{N}$ against $\mathbf{S}^{(b)} + \mathbf{N}$, with a, b any single integers in the range $(1 \le a, b \le N)$, $(a \ne b)$, $N = 2$, is readily treated. From (18) we write for the decision process

$$\left.\begin{array}{lll} \text{decide } \gamma_a: & \mathbf{S}^{(a)} + \mathbf{N}, & \text{if } \Lambda_a(\mathbf{V}) > \Lambda_b(\mathbf{V})K_a^{(b)} \\ \text{decide } \gamma_b: & \mathbf{S}^{(b)} + \mathbf{N}, & \text{if } \Lambda_a(\mathbf{V}) < \Lambda_b(\mathbf{V})K_a^{(b)} \end{array}\right\}$$

$$\text{where } K_a^{(b)} \equiv \frac{C_a^{(b)} - C_b^{(b)}}{C_b^{(a)} - C_a^{(a)}} > 0, \tag{21}$$

which can also be expressed alternatively in terms of a single likelihood ratio

$$\Lambda_a^{(b)}(\mathbf{V}) \equiv p_b\langle W_n(\mathbf{V} - \mathbf{S}^{(b)})\rangle_b / p_a\langle W_n(\mathbf{V} - \mathbf{S}^{(a)})\rangle_a, \tag{22}$$

or its reciprocal. [Typical decision regions are shown in Fig. 1, next column, if we replace Λ_1 by Λ_a, Λ_2 by Λ_b and allow the line $L_1 - L_2 = L_a - L_b = 0$ to go through zero, with slope $(K_a^{(b)})^{-1}$.]

(b) *Ternary Detection*

In this first example we assume that noise alone is one of the three possible alternatives, so that $N = 2$. Then from (14) and (15) the decision process is found at once ($k = 1, 2; l = 1, 2$). The two thresholds $K_0^{(1)}$, $K_0^{(2)}$ are

$$\begin{aligned} K_0^{(1)} &= \frac{\lambda_2^{(0)}\lambda_1^{(2)} - \lambda_1^{(0)}\lambda_2^{(2)}}{\Delta}; \\ K_0^{(2)} &= \frac{\lambda_1^{(0)}\lambda_2^{(1)} - \lambda_1^{(1)}\lambda_2^{(0)}}{\Delta}; \\ \Delta &= \lambda_1^{(1)}\lambda_2^{(2)} - \lambda_1^{(2)}\lambda_2^{(1)}, \end{aligned} \tag{23}$$

and we decide

$$\gamma_0: \mathbf{N}, \quad \left.\begin{array}{l} \text{when } \lambda_1^{(0)} + \lambda_1^{(1)}\Lambda_1 + \lambda_1^{(2)}\Lambda_2 > 0 \\ \text{and } \lambda_2^{(0)} + \lambda_2^{(1)}\Lambda_1 + \lambda_2^{(2)}\Lambda_2 > 0, \end{array}\right\}, \tag{24}$$

$$\gamma_1: \mathbf{S}^{(1)} + \mathbf{N}, \left.\begin{array}{l} \text{when } \lambda_1^{(0)} + \lambda_1^{(1)}\Lambda_1 + \lambda_1^{(2)}\Lambda_2 \\ \qquad < \lambda_2^{(0)} + \lambda_2^{(1)}\Lambda_1 + \lambda_2^{(2)}\Lambda_2 \\ \text{and } \lambda_1^{(0)} + \lambda_2^{(1)}\Lambda_1 + \lambda_1^{(2)}\Lambda_2 < 0 \end{array}\right\}, \tag{25}$$

$$\gamma_2: \mathbf{S}^{(2)} + \mathbf{N}, \left.\begin{array}{l} \text{when } \lambda_2^{(0)} + \lambda_2^{(1)}\Lambda_1 + \lambda_2^{(2)}\Lambda_2 \\ \qquad < \lambda_1^{(0)} + \lambda_1^{(1)}\Lambda_1 + \lambda_1^{(2)}\Lambda_2 \\ \text{and } \lambda_2^{(0)} + \lambda_2^{(1)}\Lambda_1 + \lambda_2^{(2)}\Lambda_2 < 0 \end{array}\right\}. \tag{26}$$

The boundaries of the various decision regions are easily determined from (16, 17) and the Λ_1-, Λ_2-axes bounding the first quadrant. A typical case is illustrated in Fig. 1.

The decision process is particularly simple when the case of noise alone is removed, and one of three possible combinations of signal and noise can now occur; e.g., $\mathbf{S}^{(a)} + \mathbf{N}$, $\mathbf{S}^{(b)} + \mathbf{N}$, $\mathbf{S}^{(c)} + \mathbf{N}$ $(a \ne b \ne c)$, $(1 \le a, b, c \le N)$, $N = 3$. From (18) we find the decision process:

$$\textit{decide } \gamma_a: \mathbf{S}^{(a)} + \mathbf{N}, \text{ when } \left.\begin{array}{l} \Lambda_a > \Lambda_b K_{ab}^{(b)} + \Lambda_c K_{ab}^{(c)} \\ \Lambda_a > \Lambda_b K_{ac}^{(b)} + \Lambda_c K_{ac}^{(c)} \end{array}\right\}, \tag{27}$$

decide γ_b: $\mathbf{S}^{(b)} + \mathbf{N}$, according to (27), replacing a by b, and b by a therein. (28)

decide γ_c: $\mathbf{S}^{(c)} + \mathbf{N}$, according to (27), letting $a \to c$, $b \to a$, $c \to b$ therein, (29)

where the thresholds $K_{ab}^{(b)}$ etc., are specifically

$$\begin{aligned} K_{ab}^{(b)} &\equiv \frac{C_a^{(b)} - C_b^{(b)}}{C_b^{(a)} - C_a^{(a)}}; \quad K_{ab}^{(c)} \equiv \frac{C_a^{(c)} - C_b^{(c)}}{C_b^{(a)} - C_a^{(a)}}; \\ K_{ac}^{(b)} &\equiv \frac{C_a^{(b)} - C_c^{(b)}}{C_c^{(a)} - C_a^{(a)}}; \quad K_{ac}^{(c)} \equiv \frac{C_a^{(c)} - C_c^{(c)}}{C_c^{(a)} - C_a^{(a)}}. \end{aligned} \tag{30}$$

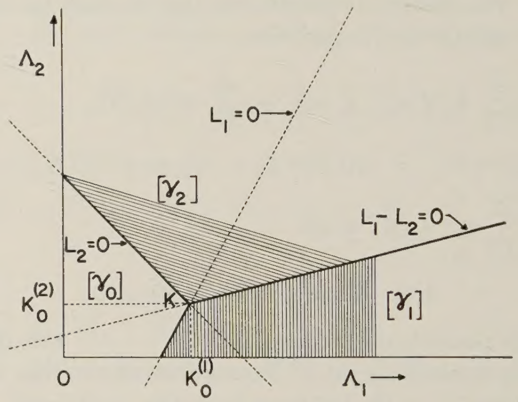

Fig. 1—Regions of decision for ternary detection ($N = 2$): $\mathbf{N}$ vs. $\mathbf{S}^{(1)} + \mathbf{N}$ vs. $\mathbf{S}^{(2)} + \mathbf{N}$. ($\lambda_1^{(2)} > 0$; $\lambda_2^{(1)} < 0$.)

[The thresholds for γ_b, γ_c are found by interchanging a, b, c according to (28), (29), respectively.] The bounding surfaces follow from (19) and the planes defining the first *octant* (in Λ_a, Λ_b, Λ_c-space), are shown for a typical case in Fig. 2 (opposite). A variety of different regions are clearly possible in these ternary cases, depending on our choice of the preassigned costs, subject to (7), of course.

(c) *Simple* ($N + 1$)*-ary Detection*

A particular case of considerable interest and simplicity (as far as the structure of the detector, e.g., (14), (15), or (18), is concerned) occurs when we assign the *same* constant costs $\mathcal{C}_0$ (> 0) to all types of "failure," and zero costs to all types of "success". Then (9) becomes $\lambda_k^{(0)} = \mathcal{C}_0$, $\lambda_k^{(l)} = 0$ $(l \ne k)$; $\lambda_k^{(k)} = -\mathcal{C}_0$, and the decision process (14), (15) is governed simply by the inequalities:

$$\text{de } \gamma_k: \quad \left.\begin{array}{l} \text{If} \quad \Lambda_k(\mathbf{V}) \geq \Lambda_j(\mathbf{V}), \\ \qquad \text{all } (j \neq k); \quad (j = 1, \cdots N) \\ \Lambda_k(\mathbf{V}) \geq 1 \end{array}\right\}, \tag{31}$$

each $k(= 1, \cdots N)$ in turn. For noise alone (15) is ply

$$\text{de } \gamma_0: \quad \text{if} \quad \Lambda_k(\mathbf{V}) \leq 1, \qquad (\text{all } k = 1, \cdots N). \tag{32}$$

e boundaries of the decision regions are obtained as ore from (16, 17), in terms of the equalities above. For ary detection, when the case "noise-alone" is removed, first line of (31) provides the desired inequalities, and boundaries of the decision regions again follow from indicated equalities, see (19).

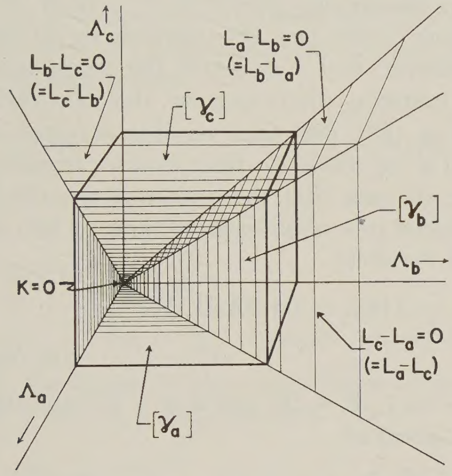

Fig. 2—Regions of decision for ternary detection ($N = 3$): $\mathbf{S}^{(a)} + \mathbf{N}$ vs. $\mathbf{S}^{(b)} + \mathbf{N}$ vs. $\mathbf{S}^{(c)} + \mathbf{N}(a, b, c \geq 1)$.

ROBABILITIES OF DECISION ERRORS, AVERAGE RISK AND INFORMATION LOSS

While the section on minimization of average risk es the structure of the detector and the decision process, choose suitable thresholds and even to make suitable t assignments, it is often necessary to know the error babilities, and to assess their effects on performance computing the average risk. Now with each possible orrect decision we may define a conditional probability error, according to

$$\alpha_k^{(0)} \equiv \int_\Gamma \delta(\gamma_k \mid \mathbf{V}) F(\mathbf{V} \mid \mathbf{S}^{(0)})\, d\mathbf{V} \tag{33}$$

$\equiv$ cond. prob. of calling null signal any one member of kth signal class, $(k = 1, \cdots N)$

$$\langle \beta_j^{(k)} \rangle_k \equiv \int_\Gamma \delta(\gamma_j \mid \mathbf{V}) \langle F(\mathbf{V} \mid \mathbf{S}^{(k)}) \rangle_k \, d\mathbf{V} \tag{34}$$

$\equiv$ cond. prob. of calling any one member of the kth signal class a member of the jth signal class (in noise). $(j \neq k; j = 0, \cdots N, k = 1, \cdots N)$

The conditional probability of correctly deciding that any one signal member of class k is present in noise $(k = 1, \cdots N)$ is

$$\langle \eta_k^{(k)} \rangle_k \equiv \int_\Gamma \delta(\gamma_k \mid \mathbf{V}) \langle F(\mathbf{V} \mid \mathbf{S}^{(k)}) \rangle_k \, d\mathbf{V} \tag{35}$$

$$= 1 - \sum_{j=1}^{N}{}' \langle \beta_j^{(k)} \rangle_k . \tag{35a}$$

In the situation where the case "noise alone" is removed, we have $\langle \beta_j^{(k)} \rangle_k$, $(j \neq k)$; $(j, k = 1, \cdots N)$.

It is convenient now to make a change of variable and consider some monotonic function of the Λ_k's as our new independent variables, since it is in terms of the Λ's that the decision regions for $\gamma_0, \cdots, \gamma_N$ are explicitly given. A simple choice of particular utility is $x_k = \log \Lambda_k$, $(k = 1, \cdots, N)$, so that (33, 34) may now be written

$$\alpha_k^{(0)} = \int_{[x_1]} \cdots \int_{[x_N]} Q_n(x_1, \cdots, x_N)\, dx_1 \cdots dx_N, \tag{36}$$

$$\langle \beta^{(k)} \rangle_k = \int_{[x_1]} \cdots \int_{[x_N]} P_n^{(k)}(x_1, \cdots, x_N)\, dx_1 \cdots dx_N, \qquad (P_n^{(0)} = Q_n), \tag{37}$$

where Q_n, $P_n^{(k)}$ are the *joint probability densities* for the random variables $\log \Lambda_1, \cdots, \log \Lambda_N$, in the first instance with respect to the null hypothesis H_0, and in the second, with respect to the alternatives H_k. Here $[x_k]$ signifies the decision region for x_k (some typical cases are illustrated in Figs. 1 and 2, for the transformation $x_k' = \Lambda_k$, rather than $x_k = \log \Lambda_k$.) These probability densities may be written in terms of the original $\mathbf{V}$ for additive and independent signal and noise as

$$Q_n(x_1, \cdots, x_N) = \int_\Gamma W_n(\mathbf{V}) \prod_{i=1}^{N} \delta(x_i - \log \Lambda_i)\, d\mathbf{V} \tag{38}$$

$$P_n^{(k)}(x_1, \cdots, x_N) = \int_\Gamma \langle W_n(\mathbf{V} - \mathbf{S}^{(k)}) \rangle_k \prod_{i=1}^{N} \delta(x_i - \log \Lambda_i)\, d\mathbf{V}. \tag{39}$$

(A specific example in the gauss case is given in the following section.)

With (33)-(36), we can now write the average risk (8) or (12), minimized or not, as

$$R_N(\sigma, \delta) = \mathcal{R}_0 + q \sum_1^N \lambda_k^{(0)} \alpha_k^{(0)} + \sum_{k,l=1}^{N}{}'^{(k \neq l)} p_k \lambda_l^{(k)} \langle \beta_l^{(k)} \rangle_k + \sum_{k=1}^{N} p_k \lambda_k^{(k)} \eta_k^{(k)}, \tag{40}$$

which for the case of the excluded null signal simply omits the terms in $\lambda_k^{(0)}$, and sets $\mathcal{R}_0 = 0$, with $\lambda_k^{(l)}$, $(k, l \geq 1)$ equal to the costs $C_k^{(l)} \geq 0$. The expressions (36, 37) for the error probabilities appearing in (40) have particularly simple limits for $[x_k]$ when we make the $(\mathcal{C}_0, 0)$ cost assumptions of example 3(c) above. We easily find that now (the primes indicate terms $j = k$ omitted in product):

$$\alpha_k^{(0)} = \int_0^\infty dx_k \left\{ \prod_{j=1}^{N}{}' \int_{-\infty}^{x_k} dx_j \right\} Q_n(x_1, \cdots, x_N), \quad (k = 1, \cdots N) \tag{41}$$

$$\langle \beta_j^{(k)} \rangle_k = \int_0^\infty dx_j \left\{ \prod_{l=1}^{N}{}' \int_{-\infty}^{x_j} dx_l \right\} P_n^{(k)}(x_1, \cdots, x_N), \quad (j \neq k; j, k \geq 1), \tag{42}$$

and

$$\langle \beta_0^{(k)} \rangle_k = \int_{-\infty}^0 dx_1 \cdots \int_{-\infty}^0 dx_N \, P_n^{(k)}(x_1, \cdots, x_N). \tag{43}$$

When the noise class is omitted, (41) and (43) do not apply, and the lower limit on the first integral of (42) becomes $-\infty$ instead of 0. For the general cost assumptions (9) we must use (16, 17), or (19), all k, to specify the boundaries on Λ_k and hence on $\log \Lambda_k$. General results for the ternary case (Example 3(b)) follow at once from (24-26) or (27-29) with the aid of Figs. 1 and 2.

Once the $\alpha_k^{(0)}$, $\langle \beta_j^{(k)} \rangle_k$ have been found for our optimum system, we can assess its performance not only from the risk point of view, e.g., (40) but also determine the average information loss or *equivocation* which inevitably occurs when a definite decision is made under the present conditions of noise and finite observation periods. The actual amount of information conveyed, on the average, is

$$H_T = -H(\sigma, \delta) - q \log q - \sum_{i=1}^{N} p_i \log p_i, \tag{44}$$

and the equivocation $H(\sigma, \delta)$ may be computed from the definition of the α's, β's, p's, etc., to be[9]

$$H(\sigma, \delta) = -\sum_{i=0}^{N} \sum_{j=0}^{N} P(\gamma_i, S_j) \log [P(\gamma_i, S_j)/P(\gamma_i)], \tag{45}$$

where

$$P(\gamma_i, S_j) = p_j \beta_i^{(j)} (j \neq 0), \quad \text{or} \quad q\alpha_i^{(0)}, \quad (j = 0), \tag{46}$$

and

$$P(\gamma_i) = \begin{cases} q\alpha_i^{(0)} + p_i(1 - \sum_{k \neq i} \beta_k^{(i)}) + \sum_{\substack{j \neq i \\ j \neq 0}} p_{ii}^{(j)}, \ (i \neq 0), \\ \text{or} \\ \sum_{j \neq 0} p_j \beta_0^{(j)} + q(1 - \sum_{k \neq 0} \alpha_k^{(0)}), \ (i = 0). \end{cases} \tag{47}$$

Following section illustrates above discussion, with specific example involving an optimum $(N + 1)$-ary decision:

An Example

Let us consider the situation in which the null signal, or any one of N arbitrary, non-zero signals (and noise), identical in structure but differing in amplitude, may be present at the input. Detection is assumed to be *coherent*,[2] the signals and noise are additive, and the costs of correct and incorrect decisions are taken to be zero and unity respectively. The noise itself is assumed gaussian, with a known variance matrix, see (67) *et seq.*, and we wish the explicit structure of the optimum detector, with the associated minimum average risk. Here we make use of the specific distributions $P_n^{(k)}$ and Q_n derived for this case in the Appendix below.

The kth hypothesis class contains but one signal, of amplitude a_{0k}. Let us accordingly order the amplitudes for $(k = 1 \cdots N)$: $0 < a_{01} < a_{02} \cdots < a_{0k} < \cdots a_{0N}$, and observe from (75) *et seq.*, that the signal matrix $\mathbf{S}_N$ becomes here specifically

$$\mathbf{S}_N = \Phi_n(s, s) \, || \, a_{0i} \quad a_{0j} \, || = \Phi_n(s, s) \mathbf{a}_0 \mathbf{a}\dagger_0, \tag{48}$$

where $\mathbf{a}_0$ is the column vector $[a_{01}, \cdots a_{0N}]\dagger$, $\Phi_n(s, s)$ is the structure factor [see 68] common to all the signals in this example, and $\dagger$ indicates the transposed matrix. Since the matrix $a_0 \, a\dagger_0$ is singular, the joint distributions Q_n, P_n, as in (77), (80) take on special forms which are best found if we return to their Fourier transforms (76), (79). Here we note that the quadratic from $\boldsymbol{\xi}\dagger \, (\mathbf{a}_0 \, \mathbf{a}\dagger_0) \, \boldsymbol{\xi}$ can be reduced to a *single* squared term by two successive changes of variable:

$$\boldsymbol{\xi}\dagger(\mathbf{a}_0\mathbf{a}\dagger_0)\boldsymbol{\xi} = \mathbf{Z}\dagger\mathbf{A}\mathbf{Z} = \mathbf{U}\dagger\mathbf{c}\dagger\mathbf{A}\mathbf{c}\mathbf{U} = U_l^2, \quad (l = 1, \cdots, \text{or } N), \tag{49}$$

where $Z_i = a_i \xi_i$, $\mathbf{Z} = \mathbf{cU}$, and $\mathbf{A} = || \, 1 \, ||$, and the (NXN) matrix $\mathbf{c}$ is given by

$$\mathbf{c} = \begin{Vmatrix} 1 & 0 & \cdots & & & \cdots & 0 \\ 0 & 1 & & & & & \\ 0 & & \ddots & & 0 & & \\ -1 & -1 & \cdots & -1 + 1 & -1 & \cdots & -1 \\ \vdots & & 0 & & \ddots & & 0 \\ 0 & \cdots & & & & \cdots & 1 \end{Vmatrix} \leftarrow l\text{th row} \quad (\text{any } l = 1, \cdots, N) \tag{50}$$

Eq. (77) for $Q_n(\mathbf{y})$ then becomes

$$Q_n(\mathbf{y}) = a_{0l}^{-1} \int_{-\infty}^{\infty} [\exp \{-(1/2)u_l^2 \Phi_n(s, s) - iu_l y_l / a_{0l}\}] \frac{du_l}{2\pi} \cdot \prod_{j=1}^{N}{}' a_{0j}^{-1} \int_{-\infty}^{\infty} \exp \{iu_j(y_l/a_{0l} - y_j/a_{0j})\} \frac{du_j}{2\pi},$$

$$= a_{0l}^{-1}(2\pi\Phi)^{-1/2} \exp [-y_l^2/2a_l^2\Phi] \prod_{j=1}^{N} \delta(y_j - a_{0j}y_l/a_{0l}), \tag{51}$$

where the prime now indicates that the lth factor in the product is omitted. The result for $P_n^{(k)}$ $(\mathbf{y})$ is the same with y_j replaced by $y_j - a_{0j}a_{0k} \, \Phi$ in (51).

The error probabilities (81)-(83) are next found with the help of (51) and the expression for $P_n^{(k)}$. First evaluating the integrals involving the delta functions, we find that

[9] For the expression for equivocation in the binary case, see D. Middleton, "Information loss attending the decision operation in detection," *Jour. Appl. Phys.*, vol. 25, p. 127; 1954.

$$\int_{-\infty}^{y_l+A_l-A_j} \delta(y_j - a_{0j}y_l/a_{0l})\, dy_j = \begin{cases} 1, & \text{for } a_0 y_l/a_{0l} < y_l + A_l - A_j \\ 0, & \text{otherwise.} \end{cases} \tag{52}$$

The inequality on the right is equivalent to

$$y_l < C_{lj} \quad (j > l); \qquad y_l > C_{lj} \quad (j < l), \tag{53}$$

where

$$C_{lj} \equiv \tfrac{1}{2}a_{0l}(a_{0j} + a_{0l})\Phi_n(s, s) + [a_{0l}/(a_{0j} - a_{0l})] \log [\mu_l/\mu_j], \quad (a_{0l} \neq a_{0j}). \tag{54}$$

The product Π_j' of integrals (52) which appears in (81)-(83) is thus unity over a range of y_l extending from the *lower limit* $C_{l-} \equiv \mathrm{Max}_j\, C_{lj}$, $(j < l)$, to the *upper limit* $C_{l+} \equiv \mathrm{Min}_j\, C_{lj}$, $(j > l)$, and is zero outside this interval.

With the arbitrary index l set equal to j, for convenience, (81)-(83) become finally

$$\alpha_j^{(0)} = a_{0j}^{-1}(2\pi\Phi)^{-1/2} \int_{(C_{j-}\text{ or }-A_j)}^{C_{j+}} \exp(-y^2/2a_{0j}^2\Phi)\, dy, \tag{55}$$

and

$$\langle\beta_j^{(k)}\rangle = a_{0j}^{-1}(2\pi\Phi)^{-1/2} \int_{(C_{j-}\text{ or }-A_j)}^{C_{j+}} \exp[-(y - a_{0j}a_{0k}\Phi)^2/2a_{0j}^2\Phi]\, dy, \tag{56}$$

in which the *larger* of the lower limits is to be used. Similarly, with $l = k$, (82) becomes

$$\langle\beta_0^{(k)}\rangle = a_{0k}^{-1}(2\pi\Phi)^{-1/2} \int_{-\infty}^{C_{0+}} \exp[-(y - a_{0k}^2\Phi)^2/2a_{0k}^2\Phi]\, dy, \tag{57}$$

with

$$C_{0+} = \min j\, [a_{0k}a_{0j}\Phi/2 - a_{0k} \log \mu_j/a_{0j}], \quad (j \neq k).$$

To show how these relations may be used in a simple case, let us assume the amplitudes to be uniformly spaced, so that $a_{0j} = j\Delta$, where Δ is the (normalized) "quantization" interval, and let us assume also equal *a priori* probabilities, so that $\mu_j = 1$ $(j = 1, \cdots, N)$. Eqs. (55)-(57) now easily reduce to[10]

$$\alpha_j^{(0)} = \tfrac{1}{2}\{\Theta[(j + 1/2)d] - \Theta[(j - 1/2)d]\}, \quad (j = 1, \cdots, N - 1), \tag{58}$$

$$\alpha_N^{(0)} = \{1 - \Theta[(N - 1/2)d]\}/2, \tag{59}$$

$$\beta_j^{(k)} = \tfrac{1}{2}\{\Theta[(j - k + 1/2)d] - \Theta[(j - k - \tfrac{1}{2})d]\},$$

$$\begin{Bmatrix} j = 1, \cdots, N - 1 \\ k = 1, \cdots, N \end{Bmatrix}, \quad (j \neq k), \tag{60}$$

$$\beta_N^{(k)} = \{1 - \Theta[(N - k - 1/2)d]\}/2, \quad (k = 1, \cdots, N - 1), \tag{61}$$

$$\beta_N^{(k)} = \{1 - \Theta[(k - 1/2)d]\}/2, \quad (k = 1, \cdots, N), \tag{62}$$

where $d \equiv \Delta\, [\Phi(s, s)/2]^{1/2}$ and $\Theta(x) = (2/\pi^{1/2}) \int_0^x e^{-y^2}\, dy$ is the familiar error integral. Since the N signals (and noise alone) have equal *a priori* probabilities in this example, we write $p_k = q = (N + 1)^{-1}$, $k = 1 \cdots N$. Because of the simple cost assignment, the Bayes risk here becomes the product of $(N + 1)^{-1}$ and the sum of the error probabilities (58)-(62). Noting that

$$\sum_1^N \alpha_j^{(0)} = \sum_0^{N-1} \beta_j^{(N)} = (1/2) \sum_{j=0}^{N}{}' \beta_j^{(k)} = [1 - \Theta(d/2)]/2, \quad (k = 1, \cdots N - 1), \tag{63}$$

we find minimum average (or Bayes) risk now simply

$$R_N(\sigma, \delta) = \frac{N}{N + 1} \{1 - \Theta(d/2)\}, \quad (N \geq 1). \tag{64}$$

We observe from (64) that the shape of the Bayes risk curve (*vs.*d) is independent of the number of hypotheses or signals, the latter entering merely as a scale factor. Moreover, as N is increased, the absolute Bayes risk becomes entirely independent of the number of possible signals. This is a consequence of the simple costs, *a priori* signal probabilities, and signal structure assumed in this example, but is clearly not true in general. Thus, as N is increased the number of different kinds of error increases as N^2, but here sum of error probabilities increases only as N. Since average risk equals $(N + 1)^{-1}$ times latter, it becomes essentially independent of N for, say, $N > 10$.

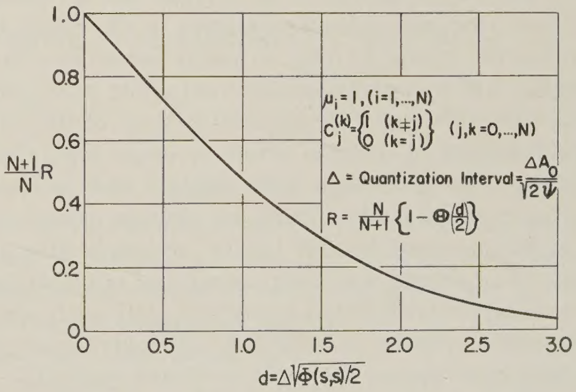

Fig. 3—Bayes risk for the coherent multiple alternative detection of N signals in Gaussian noise.

Fig. 3, above, shows variation of Bayes risk with d. As quantization interval becomes larger, the risk approaches zero as expected, since the more widely separated the signal amplitudes, the easier it is to discriminate among them.

[10] These results may alternatively be derived from the basic inequalities (14) defining the optimum detector. One notes that for this specific case all of the likelihood ratios depend upon the single random variable $\Phi(v, s)$, (69). It is therefore merely necessary to calculate the (one-dimensional) distribution of this quantity, after which the inequalities (14) give directly the limits on the integrals defining the errors. Usually, however, the multiple integrals by which P, Q, and the error probabilities are defined, do not "fold" conveniently, and the general approach of the previous section must be used.

The dependence of d on the number of samples taken (or on T, the length of the sampling period if continuous sampling is used) is governed by the structure factor $\Phi(s, s)$, as in (68). For example, if the samples are uncorrelated, $\Phi(s, s)$ is proportional to T, and $d \backsim \Delta T^{\frac{1}{2}}$. Thus, for a given N, if the *minimum detectable quantization interval* $\Delta_{\min}$ is defined as the Δ corresponding to some fixed fraction of the risk R (see the discussion of minimum detectable signal in reference 1), we note that $\Delta_{\min} \backsim T^{-1/2}$, which is characteristic of coherent detection in general[2].

Finally, if "noise alone" is excluded as a possible input condition, so that detection becomes the process of distinguishing among N (≥ 2) *nonzero* signals, Equations (58), (59), (62) no longer apply. Equations (60), (61) still hold, however, except when $j = 1$, in which case we have the new relation $\beta_1^{(k)} = \{1 - \text{Ⓗ}[(k - 3/2)d]\}/2$. The sums of the error probabilities may be found as before; the results are

$$\sum_2^N \beta_j^{(1)} = \sum_1^{N-1} \beta_j^{(N)} = (1/2) \sum_{j=1}^N \beta_j^{(k)}$$
$$= \{1 - \text{Ⓗ}(d/2)\}/2, \quad (k = 2, \cdots, N-1). \tag{65}$$

The Bayes risk is then easily shown to be

$$R_N(\sigma, \delta) = \left(\frac{N-1}{N}\right)\{1 - \text{Ⓗ}(d/2)\}, \quad (N \geq 2), \tag{66}$$

which is *identical* with the corresponding result (64) for the *same* number of alternatives. In each case, Fig. 3 may be used with the appropriate scale factor to find absolute risks or minimum detectable quantization intervals.

Conclusion

We have given the general structure of the optimum detector when one of an arbitrary number of different possible signals (including noise alone) may be present. The evaluation of the minimum average risk is indicated, and illustrated with a simple example in the N-ary case. However, the treatment is by no means limited to coherent detection and hypothesis classes containing but a single signal. The extension of the detailed analysis of the section on probabilities of decision errors, average risk, and information loss to include weak signals and incoherent reception may be made directly by obvious extensions of the technique used in the binary or single-alternative theory[2]. For general cost assignments and multiple signal types, analytical difficulties increase rapidly with number of hypothesis classes, as expected, although ternary and quarnary cases appear tractable by direct methods.

Appendix

Distributions of log Λ_k for Coherent Detection in Normal Noise

As an example of some interest, let us obtain the density functions Q_n, $P_n^{(k)}$ when a set of arbitrary and distinguishable signals $\mathbf{S}^{(k)}$, $(k = 1, \cdots, N)$ are detected coherently[2] in additive normal random noise, with the additional constraint that each signal class ($k \geq 1$) contains but one member. For this situation it is possible to specify Q_n, $P_n^{(k)}$ in closed form for all signal strengths and for arbitrary waveforms. We begin by writing

$$\langle W_n(\mathbf{V} - \mathbf{S}^{(k)})\rangle_k = (2\pi)^{-n/2} \mid \mathbf{K} \mid^{-1/2}$$
$$\cdot \exp\{-\tfrac{1}{2}[\mathbf{V}\dagger\mathbf{K}^{-1}\mathbf{V} - 2\mathbf{V}\dagger\mathbf{K}^{-1}\mathbf{s}_k a_{0k}\psi^{1/2} + a_{0k}^2\psi\mathbf{s}\dagger_k\mathbf{K}^{-1}\mathbf{s}_k]\}, \tag{67}$$

where we have made the usual normalization:[1,2] $\mathbf{S}^{(k)} = \psi^{1/2} a_{0k}\mathbf{s}_k$, with $a_{0k} \equiv A_{0k}/(2\psi)^{1/2}$. Here A_{0k} is an amplitude scale factor for the kth signal; $\psi = \langle V_N^2\rangle$, the mean noise intensity; $\mathbf{K}$ is the *variance matrix* $\| \langle (V_N)_l \; (V_N)_m\rangle \|$ $(l, m = 1, \cdots, n)$ where $\langle V_N\rangle = 0$ here; $\mathbf{V}$ is a column vector, and $\mathbf{V}\dagger$ its transpose, while $\mid \mathbf{K} \mid$ is the determinant of the $(n \times n)$ symmetrical matrix $\mathbf{K}$. Normalizing $\mathbf{V}$ according to $\mathbf{V} = \psi^{1/2}\mathbf{v}$, and writing[11]

$$\mathbf{v}\dagger\mathbf{K}^{-1}\psi\mathbf{s}_j \equiv \Phi_n(v, s_j); \quad \mathbf{s}\dagger_j\mathbf{K}^{-1}\psi\mathbf{s}_j \equiv \Phi_n(s_j, s_j), \tag{68}$$

we find that log Λ_j ($\mathbf{V}$), cf. (10) in (38), (39), becomes

$$\log \Lambda_j = \log \mu_j + a_{0j}\Phi_n(v, s_j) - a_{0j}^2\Phi_n(s_j, s_j)/2,$$
$$(j = 1, \cdots, N), \quad \mu_j \equiv p_j/q. \tag{69}$$

Since

$$\delta(x_j - \log \Lambda_j) = \int_{-\infty}^{\infty} \exp[-i\xi_j(x_j - \log \Lambda_j)]\, d\xi_j/2\pi, \tag{70}$$

we can apply this to (38), use the transformation $y_j = x_j - \log \mu_j + a_{0j}^2\,\Phi_{jj}/2 \equiv x_j - A_j$ (whose Jacobian is clearly unity), and in place of Q_n $(x_1 \cdots x_N)$ write

$$Q_n(y_1 \cdots y_N) = \int_\Gamma W_n(\mathbf{V})\, d\mathbf{V}$$
$$\cdot \int_{-\infty}^{\infty} \cdots \int \exp\left((-i) \sum_1^N \xi_j y_j\right)$$
$$\cdot \exp\left(+\sum_1^N i a_{0j}\xi_j \mathbf{v}\dagger(\mathbf{K}^{-1}\psi\mathbf{s}_j\right) d\xi_1 \cdots d\xi_N\, (2\pi)^{-N}, \tag{71}$$

where W_n ($\mathbf{V}$) is found from (67) on setting $\mathbf{s} = 0$. Furthermore,

$$F_{y_1 \cdots y_N}(\xi_1 \cdots \xi_N)_Q$$
$$= \int_{-\infty}^{\infty} \cdots \int \exp[i\boldsymbol{\xi}\dagger\mathbf{y}] Q_n(y_1 \cdots y_N)\, dy_1 \cdots dy_N \tag{72}$$
$$= \int_{-\infty}^{\infty} \cdots \int (2\pi)^{-N/2} \mid \mathbf{K}\psi^{-1} \mid^{-1/2} dv_1 \cdots dv_N$$
$$\cdot \exp[-(1/2)\mathbf{v}\dagger\mathbf{K}^{-1}\mathbf{v} + i\mathbf{v}\dagger\boldsymbol{\lambda}(\xi)], \tag{73}$$

is the *characteristic function* corresponding to the distribution density $\mathbf{Q}_n$, and (73) follows from (71). The column vector $\boldsymbol{\lambda}$ is $\boldsymbol{\lambda}(\xi) = \sum_{j=1}^N a_{0j}\, \xi_j\, (\mathbf{K}^{-1}\, \psi)\mathbf{s}_j$. The

[11] Notation is that of second and third papers of reference 2.

tegral (73) is readily evaluated[12] to give

$$F_{\mathbf{y}}(\xi_1 \cdots \xi_N)_Q = \mathrm{e}\,[-(1/2)\boldsymbol{\lambda}\dagger(\xi)(\mathbf{K}/\psi)\boldsymbol{\lambda}(\xi)], \quad (74)$$

here

$$\boldsymbol{\lambda}\dagger\mathbf{K}\psi^{-1}\boldsymbol{\lambda} = \sum_{j=1}^{N}\sum_{l=1}^{N} a_{1j}a_{0l}\xi_j\xi_l[\mathbf{s}\dagger_j\mathbf{K}^{-1}\psi\mathbf{s}_l]$$

$$= \sum_{jl}^{N} \xi_j\xi_l a_{0j}a_{0l}\sigma_{jl} = \boldsymbol{\xi}\dagger\mathbf{S}_N\boldsymbol{\xi}, \quad (75)$$

d the symmetrical (NXN) matrix $\mathbf{S}_N = \| a_{0j}\ a_{0l}$ $_j\mathbf{K}^{-1}\psi\mathbf{s}_l \| = \| a_{0j}a_{0l}\ \Phi_{jl} \| \equiv \| (S_N)_{jl} \|$. The character-tic function (74) becomes explicitly

$$F_{\mathbf{y}}(\xi_1 \cdots \xi_N)_Q = \mathrm{e}\,[-(1/2)\boldsymbol{\xi}\dagger\mathbf{S}_N\boldsymbol{\xi}], \quad (76)$$

om which the various moments of $y_1, y_2, \cdots, y_N$ are adily obtained in the usual manner by differentiation ith respect to the ξ's. The other member of the Fourier ansform pair, (72), is

$$(y_1 \cdots y_N) = \int_{-\infty}^{\infty} \cdots \int (\mathrm{e}\,[-i\boldsymbol{\xi}\dagger\mathbf{y}])$$

$$\cdot F_{\mathbf{y}}(\xi_1 \cdots \xi_N)_Q\, d\xi_1 \cdots d\xi_N/(2\pi)^N \quad (77)$$

$$= (2\pi)^{-N/2} \mid \mathbf{S}_N \mid^{-1/2} \exp\{-\tfrac{1}{2}\mathbf{y}\dagger\mathbf{S}_N^{-1}\mathbf{y}\}, \quad (78)$$

is last with the help of the literature.[12]

The distributions $P_n^{(k)}$ are obtained in the same way. ne finds finally for the characteristic function

[12] H. Cramér, "Mathemetical Methods of Statistics," Princeton niversity Press, Eq. (11-12.1a), p. 118; 1946.

$$F_{\mathbf{y}}(\xi_1 \cdots \xi_N)_P = \exp\,[i\boldsymbol{\xi}\dagger(\mathbf{S}_N)_k - \tfrac{1}{2}\boldsymbol{\xi}\dagger\mathbf{S}_N\boldsymbol{\xi}] \quad (79)$$

where $(\mathbf{S}_N)_k$ is the kth column of $\mathbf{S}_N$. The Fourier transform of this is easily shown to be[12]

$$P_n^{(k)}(y_1 \cdots y_N) = (2\pi)^{-N/2} \mid \mathbf{S}_N \mid^{-1/2}$$

$$\cdot \exp\{-\tfrac{1}{2}[\mathbf{y}\dagger - (\mathbf{S}\dagger_N)_k]\mathbf{S}_N^{-1}[\mathbf{y} - (\mathbf{S}_N)_k]\}. \quad (80)$$

Observe that because of transformation from x to y, probabilities of error (41)-(43) become specifically here

$$\alpha_j^{(0)} = \int_{-A_j}^{\infty} dy_k \left\{ \prod_{l=1}^{N}{}' \int_{-\infty}^{y_j + A_j - A_l} dy \right\} Q_n(y_1 \cdots y_N),$$

$$(j = 1, \cdots, N), \quad (81)$$

$$\langle \beta_0^{(k)} \rangle_k = \int_{-\infty}^{-A_1} dy_1 \cdots \int_{-\infty}^{-A_N} dy_N\, P_n^{(k)}(y_1 \cdots y_N),$$

$$(k = 1, \cdots, N), \quad (82)$$

$$\langle \beta_j^{(k)} \rangle_k = \int_{-A_j}^{\infty} dy_j \left\{ \prod_{l=1}^{N}{}' \int_{-\infty}^{y_j + A_j - A_l} dy_l \right\} P_n^{(k)}(y_1 \cdots y_N),$$

$$(j, k = 1, \cdots, N), \quad (j \neq k). \quad (83)$$

with (78) and (80) for Q_n, $P_n^{(k)}$. When "noise alone" is excluded as a possible input, (81), (82) do not apply, and the lower limit in (83) becomes $-\infty$ instead of $-A_j$.

The results of the section on probabilities of decision errors apply equally well for continuous sampling: matrix $\mathbf{S}_N$ is then composed of elements which are double integrals between limits $(0, T)$, instead of double sums, cf (68). (For examples, see discussion of continuous sampling in second and third papers of reference 2.)

A Note on the Envelope and Phase-Modulated Components of Narrow-Band Gaussian Noise*

ROBERT PRICE†

Summary—**The autocorrelation function and power spectrum of e phase-modulated portion of narrow-band gaussian noise is udied and specific computations are carried out for the case of a ectangular noise spectrum. Related results are given for the noise nvelope. General asymptotic expressions for the spectra are obined, together with experimental verification.**

WHEN we are dealing with a gaussian noise $n(t)$ having a narrow power spectrum $N(\omega)$ about some representative midband angular frequency p, $n(t)$ ay be represented as the product of an envelope function (t) and a phase-modulated function $y(t)$:

$$n(t) = R(t)y(t); \quad y(t) = \cos\,[pt + \theta(t)], \quad (1)$$

where Rice's definition[1] of $R(t)$ is employed. The power spectra of $R(t)$ and $y(t)$, or, equivalently, the respective autocorrelation functions $\phi_R(\tau)$ and $\phi_y(\tau)$, may be found from the autocorrelation function $\phi_n(\tau)$ of $n(t)$.[2]

Uhlenbeck[3] has shown that

$$\phi_R(\tau) = \overline{R(t)R(t+\tau)} = \phi_n(0)[2E(\sigma_\tau) - (1 - \sigma_\tau^2)K(\sigma_\tau)]$$

$$= \frac{\pi}{2}\phi_n(0)\,{}_2F_1(-1/2, -1/2; 1; \sigma_\tau^2), \quad (2)$$

* This work was supported jointly by the Army, Navy, and Air orce under contract with the Massachusetts Institute of Technology.

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[1] S. O. Rice, "Mathematical analysis of random noise," *Bell Sys. Tech. Jour.*, Vol. 23, p. 282; July, 1944. And *Bell Sys. Tech. Jour.*, Vol. 24, p. 46; January, 1945. Section 3.7.

[2] See Appendix for derivations of $\phi_R(\tau)$ and $\phi_y(\tau)$.

[3] G. E. Uhlenbeck, "Theory of the random process," MIT Radiation Lab. Report 454, October 15, 1943.

where K and E are complete elliptic normal integrals of the first and second kind, respectively, and ${}_2F_1$ is a hypergeometric function. σ_τ and $\phi_n(\tau)$ are given by

$$\sigma_\tau e^{i\lambda(\tau)} = \frac{2}{\phi_n(0)} \int_0^\infty N(\omega)e^{i(\omega-p)\tau}\,d\omega; \quad \sigma_\tau \text{ real and } \geq 0. \tag{3}$$

$$\phi_n(\tau) = \overline{n(t)n(t+\tau)} = \int_{-\infty}^{+\infty} N(\omega)e^{i\omega\tau}\,d\omega$$
$$= \phi_n(0)\sigma_\tau \cos[p\tau + \lambda(\tau)]. \tag{4}$$

Thus σ_τ may be considered to be the normalized envelope of $\phi_n(\tau)$.

Using MacDonald's result[4] for the second joint probability density of $\theta(t)$ and $\theta(t+\tau)$ we have found

$$\phi_y(\tau) = \overline{y(t)y(t+\tau)}$$
$$= \left[\frac{E(\sigma_\tau) - (1-\sigma_\tau^2)K(\sigma_\tau)}{2\sigma_\tau}\right] \cos[p\tau + \lambda(\tau)] \tag{5a}$$
$$= \frac{\pi\sigma_\tau}{8}\, {}_2F_1(1/2, 1/2; 2; \sigma_\tau^2) \cos[p\tau + \lambda(\tau)]. \tag{5b}$$

The series expansion of (5) is

$$\phi_y(\tau) = \frac{\pi\sigma_\tau}{8} \cos[p\tau + \lambda(\tau)]$$
$$\cdot \left\{1 + \sum_{i=1}^{\infty} \frac{\left[(1/2)(3/2)\cdots\left(\frac{2i-1}{2}\right)\right]^2}{i!(i+1)!} \sigma_\tau^{2i}\right\}. \tag{6}$$

Series (6) is identical, to within a proportionality constant, to a result found much earlier by Van Vleck,[5] and later by Middleton[6] and Davenport,[7] for the autocorrelation function of clipped and filtered narrow-band gaussian noise. Middleton[6] has also found the closed form (5b) for the slightly restricted case of $N(\omega)$ symmetric about p, so that substantially the only new result in the preceding is the expression of $\phi_y(\tau)$ in terms of elliptic integrals.[8]

It is worth noting that (2) and (5) also apply to cross-correlation functions between the envelopes or phase-modulated components of two noises $n_1(t)$ and $n_2(t)$ having a gaussian joint probability distribution, provided that the cross spectrum $\Phi_{12}(\omega)$ is narrow-banded about p.

$$\Phi_{12}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \overline{n_1(t)n_2(t+\tau)}\, e^{-i\omega\tau}\,d\tau. \tag{7}$$

We need only substitute, in (3) and (4), $\sqrt{\overline{n_1^2(t)}\,\overline{n_2^2(t)}}$ for $\phi_n(0)$ and $\Phi_{12}(\omega)$ for $N(\omega)$.

MacDonald[4] has remarked that the second joint probability density for the phase $\theta(t)$ appears to provide more information about the spectrum $N(\omega)$ of $n(t)$ than does the second joint probability density for the envelope $R(t)$. This observation applies to the corresponding autocorrelation functions $\phi_y(\tau)$ and $\phi_R(\tau)$, as well. Comparing (2) and (5), it is seen that $\phi_R(\tau)$ is a function of only the envelope of $\phi_n(\tau)$, while $\phi_y(\tau)$ depends on both the envelope and phase $\lambda(\tau)$. In fact, if $N(\omega)$ is symmetric about p, $\lambda(\tau)$ is 0 or π, and $\phi_n(\tau)$ can then be recovered completely from $\phi_y(\tau)$.

We have made a detailed investigation of the spectra of $y(t)$ and $R(t)$ for the particular case where $N(\omega)$ is confined to a narrow rectangular band. From this point on, all frequencies will be considered cyclic rather than angular, and all spectra double-ended. Let $n(t)$ have a uniform spectral density $N_0/2$ in the regions $(f_0 - \frac{1}{2}, f_0 + \frac{1}{2})$ and $(-f_0 - \frac{1}{2}, -f_0 + \frac{1}{2})$ and be zero elsewhere. Then

$$\phi_n(\tau) = N_0 \frac{\sin \pi\tau}{\pi\tau} \cos 2\pi f_0\tau,$$

and we find[9] for the spectrum $S_y(f)$ of $y(t)$:

$$S_y(f) = \frac{\pi}{16}\left\{u(f') + \sum_{i=M(f')}^{\infty} \frac{\left[(1/2)(3/2)\cdots\left(\frac{2i-1}{2}\right)\right]^2}{i!(i+1)!(2i)!} \cdot \sum_{j=0}^{m(i,f')} (-1)^j \binom{2i+1}{j} \left[\frac{-f'+2i+1-2j}{2}\right]^{2i}\right\}, \tag{8}$$

where $f' = 2\,\big|\,|f| - f_0\,\big|$, $\binom{2i+1}{j}$ is a binomial coefficient, and

$$u(f') = \begin{cases} 1; & f' \leq 1 \\ 0; & \text{elsewhere} \end{cases}$$

$$M(f') = \begin{cases} 1; & f' \leq 1 \\ \text{largest integer} \leq \dfrac{f'+1}{2}; & \text{elsewhere} \end{cases}$$

$$m(i, f') = \text{largest integer} < \frac{2i+1-f'}{2}. \tag{9}$$

Van Vleck[5] has found an approximation to $S_y(f)$ by using the first few terms of (8), but the convergence is poor. Likewise, he and Middleton[10] have found approximations to $S_y(f)$ for gaussian and optical $n(t)$ spectra, which may converge better. In the rectangular case, it seems easier to achieve good accuracy, at least for values of f' near the original spectral region, by performing Fourier transforms of $\phi_y(\tau)$ numerically, using the closed form (5a),

[4] D. K. C. MacDonald, "Some Statistical Properties of Random Noise," *Proc. Camb. Phil. Soc.*, Vol. 45, p. 368; 1949.

[5] J. H. Van Vleck, "The spectrum of clipped noise," Harvard RRL Report 51, July 21, 1943.

[6] D. Middleton, "Some general results in the theory of noise through nonlinear devices," *Quart. Appl. Math.*, Vol. 5, p. 445; 1948.

[7] W. B. Davenport, Jr., "Signal-to-noise ratio in bandpass limiters," *Jour. Appl. Phys.*, Vol. 24, p. 720; 1953.

[8] W. Magnus and F. Oberhettinger, "Formulas and Theorems for the Special Functions of Mathematical Physics," Chelsea Pub. Co., 1949.

[9] We have made use of D. Bierens de Haan, "Nouvelles Tables d'Integrales Definies," G. E. Stechert and Co., New York, 1939. Eq. 15, Table 159.

[10] D. Middleton, "The response of biased, saturated linear and quadratic rectifiers to random noise," *Jour. Appl. Phys.*, vol. 17, p. 778; 1946.

TABLE I

$f'/2 = \lvert \lvert f \rvert - f_0 \rvert$	$S_y(f)$
0.0	0.228
0.25	0.226
0.50	{0.219 0.0228
0.75	0.0153
1.00	0.0093
1.25	0.00495
1.5	0.00278
2.0	0.00124
2.5	0.00064

TABLE II

f	$S_R(f)/N_0$
0.0	$(\pi/2)\ \delta(f) + 0.415$
±0.25	0.315
±0.50	0.213
±0.75	0.110
±1.00	0.00675
±1.25	0.0035
±1.50	0.0016
±2.00	0.0003334
±2.50	0.0001

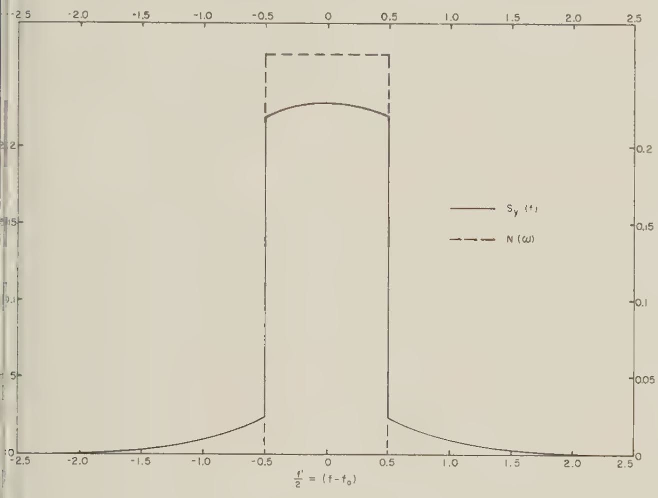

Fig. 1—Power spectrum $S_y(f)$ of $y(t)$ for rectangular $N(\omega)$.

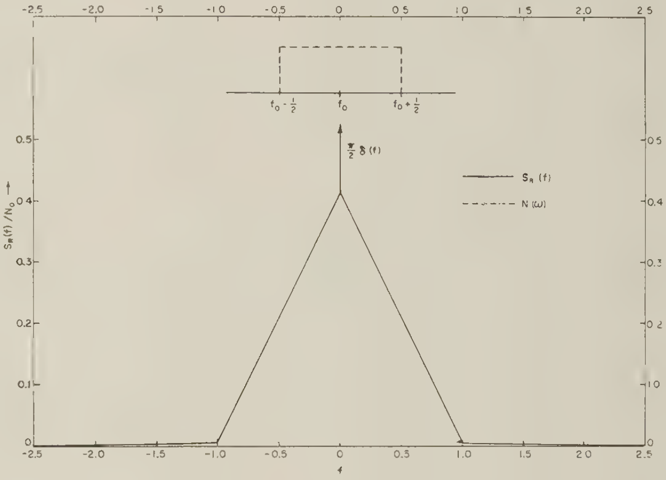

Fig. 2—Power spectrum $S_R(f)$ of $R(t)$ for rectangular $N(\omega)$.

ather than attempting to sum the series (8). Values of $_y(f)$ which have been obtained by numerical integration re presented in Table I, and a graph of $S_y(f)$ is shown in ig. 1, both above. It has been found that 89.89 per cent f the power in $y(t)$ is contained in the original spectral egion of $n(t)$.

The similarity between (2) and (5) enables the spectrum $_R(f)$ of the envelope $R(t)$ to be found with little additional bor, once the computations necessary to obtain $S_y(f)$ ave been performed. For the rectangular case considered bove, we have obtained the values of $S_R(f)$ presented in able II (opposite). Fig. 2 (opposite) is a graph of $S_R(f)$, r which an approximation has appeared elsewhere.[11] A eries similar to (8) can be developed for $S_R(f)$:

$$\frac{S_R(f)}{N_0} = \frac{\pi}{2}\left\{\delta(f) + \sum_{i=M'(f)}^{\infty} \frac{\left[(-1/2)(1/2)(3/2)\cdots\left(\frac{2i-3}{2}\right)\right]^2}{(i!)^2(2i-1)!} \cdot \sum_{j=0}^{m'(i,f)} (-1)^j \binom{2i}{j} (-\lvert f \rvert + i - j)^{2i-1}\right\} \tag{10}$$

[11] J. L. Lawson and G. E. Uhlenbeck, "Threshold Signals," vol. 24, IIT Radiation Lab. Series, McGraw-Hill Publishing Co.; 1950.

where

$$M'(f) = \text{smallest integer} > \lvert f \rvert$$
$$m'(i, f) = \text{largest integer} < i - \lvert f \rvert \tag{11}$$

and $\delta(f)$ is the Dirac δ-function.

When $N(\omega)$ is symmetric and has a finite normalized second moment A about p, asymptotic approximations to $S_y(f)$ and $S_R(f)$ can be found. The procedure is to expand (2) and (5) in power series in σ_τ and Fourier transform term-by-term, making use of the convergence of high powers of σ_τ to gaussian functions. Using Stirling's factorial approximation in the coefficients of the resulting series, and approximating the summation by integration, we obtain:

$$\lim_{f' \to \infty} S_y(f) = \frac{A}{4\pi^2 (f')^3} \tag{12}$$

$$\lim_{f \to \infty} S_R(f) = \frac{3A^2}{32\pi^4 \lvert f \rvert^5} \tag{13}$$

where

$$A = \frac{\int_p^\infty (\omega - p)^2 N(\omega)\, d\omega}{\int_p^\infty N(\omega)\, d\omega}. \tag{14}$$

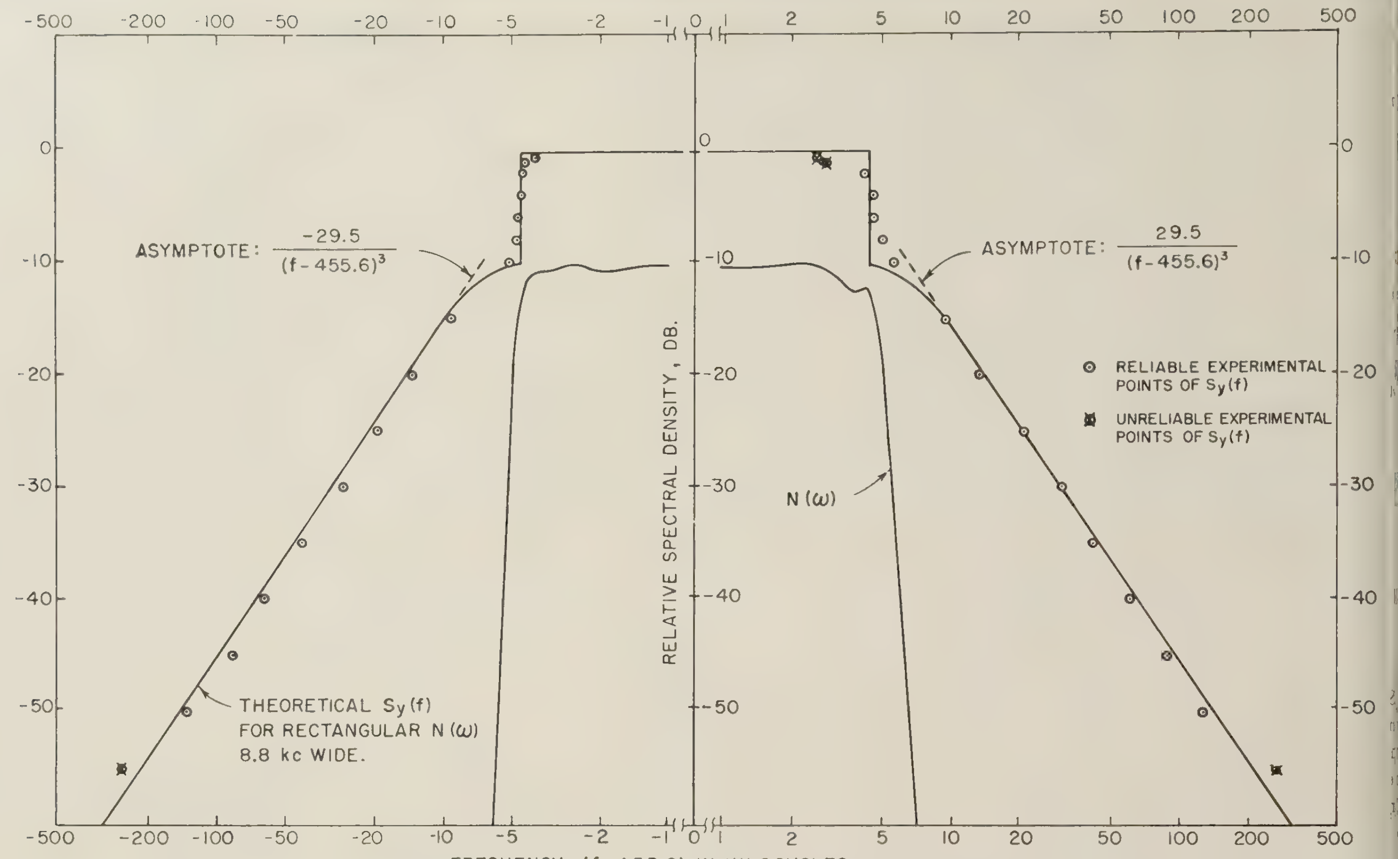

Fig. 3—Comparison of theoretical and experimental $S_y(f)$.

Comparison of (12) and (13) with the values given in Tables I and II shows that, for rectangular $N(\omega)$, these approximations are quite good, even when f' and f are not very large.

J. Craig and E. Manna, of this Laboratory, have conducted an experimental investigation of $S_y(f)$ for $N(\omega)$ having an approximately rectangular spectrum. Their results, together with the theoretical curve for an ideally rectangular $N(\omega)$ having the same normalized second moment, are presented in Fig. 3. The agreement appears to be excellent in the regions where (12) is accurate.

Appendix

Derivations of $\phi_R(\tau)$ and $\phi_y(\tau)$.

The starting point for finding $\phi_R(\tau)$ or $\phi_y(\tau)$ for narrow-band gaussian noise is given by the joint probability density distribution for the envelopes R_1, R_2 and phases θ_1, θ_2 of $n(t) = R(t)\cos[pt + \theta(t)]$ at times t_1 and $t_2 = t_1 + \tau$, respectively:[1]

$$p(R_1, R_2, \theta_1, \theta_2) = \frac{R_1R_2}{4\pi^2 A}\exp\left(-\frac{1}{2A}\{z_0R_1^2 + z_0R_2^2 - 2z_\tau R_1R_2\cos[\theta_2 - \theta_1 - \lambda(\tau)]\}\right) \tag{15}$$

where

$$A = z_0^2 - z_\tau^2; \quad z_\tau = \phi_n(0)\sigma_\tau/2 \tag{16}$$

and σ_τ and $\lambda(\tau)$ are given by (3).

$\phi_R(\tau)$ may then be found by performing the fourfold integration

$$\phi_R(\tau) = \overline{R_1R_2} = \int_0^\infty\int_0^\infty\int_{-\pi}^{+\pi}\int_{-\pi}^{+\pi} R_1R_2p(R_1, R_2, \theta_1, \theta_2)\,d\theta_1\,d\theta_2\,dR_1\,dR_2 \tag{17}$$

Rice[1] has performed the integrations over θ_1 and θ_2, obtaining

$$p(R_1, R_2) = \int_{-\pi}^{+\pi}\int_{-\pi}^{+\pi} p(R_1, R_2, \theta_1, \theta_2)\,d\theta_1\,d\theta_2 = \frac{R_1R_2}{A}I_0\left(\frac{R_1R_2}{A}z_\tau\right)\exp\left(-\frac{z_0[R_1^2 + R_2^2]}{2A}\right) \tag{18}$$

where I_0 is the modified Bessel function of the first kind, of zero order. Using elliptic integrals, Uhlenbeck[3] has carried out the remaining two integrations to obtain (2).

$\phi_y(\tau)$ may similarly be found, after first noting that

$$\phi_y(\tau) = \overline{y(t)y(t+\tau)} = \frac{\cos[p\tau + \lambda(\tau)]}{2}\overline{\cos[\theta_1 - \theta_2 + \lambda(\tau)]} \tag{19}$$

by using trigonometric expansions in (1) and averaging.

hus

$$(\tau) = \frac{\cos[p\tau + \lambda(\tau)]}{2}$$
$$\cdot \int_0^\infty \int_0^\infty \int_{-\pi}^{+\pi} \int_{-\pi}^{+\pi} \cos[\theta_1 - \theta_2 + \lambda(\tau)]$$
$$\cdot p(R_1, R_2, \theta_1, \theta_2)\, d\theta_1\, d\theta_2\, dR_1\, dR_2 \quad (20)$$

acDonald[4] has performed the integrations over R_1 and R_2, obtaining

$$p(\theta_1, \theta_2) = \int_0^\infty \int_0^\infty p(R_1, R_2, \theta_1, \theta_2)\, dR_1\, dR_2$$

$$= \frac{A}{4\pi^2 z_0^2} \frac{(1-\beta^2)^{1/2} + \beta\left(\frac{\pi}{2} + \sin^{-1}\beta\right)}{(1-\beta^2)^{3/2}}, \quad (21)$$

where

$$-\frac{\pi}{2} \le \sin^{-1}\beta \le \frac{\pi}{2} \text{ and } \beta = (z_\tau/z_0)\cos[\theta_1 - \theta_2 + \lambda(\tau)].$$

The results (5a) and (5b) are obtained by performing the remaining two integrations.[12]

[12] Details may be found in R. Price, "Some Results in the Study of Narrow Band Gaussian Noise," MIT Lincoln Lab. Technical Report No. 75, Jan. 26, 1955.

Error Bounds in Noisy Channels Without Memory*

AMIEL FEINSTEIN†

Summary—It is shown that for any noisy channel without memory having only a finite number of received signals, the error in transmitting information at a rate $H < C$ and using uniformly good codes of length n is bounded by an expression $Fe^{-Bn(C-H)^2}$ where F and B are constants depending upon the channel parameters but not upon H or n.

Introduction

IT HAS BEEN known since 1948 that, given a channel having capacity C, it is possible to transmit information through the channel at any rate less than C and to receive this information with an arbitrarily small probability of error. There are two general methods of constructing codes which will achieve this. One is the method used by Shannon in his first papers on information theory.[1] The second was given by the present author in his doctoral thesis.[2] Both methods show that by using "codes" in which the "code words" are sequences of increasing length n, the probability of reception error for any fixed rate of transmission $H < C$ goes to zero as n goes to infinity. Except for a very few specific cases, however, no general estimate of the rate of approach of the error to zero has appeared.

Derivation

Let $\{X, Y, p(y \mid x)\}$ be a channel without memory, with capacity C. Then it is known[2] that for any $H < C$ and $e > 0$ we can find $n(e, H)$, such that for each $n \ge n(e, H)$ we can find more than 2^{nH} sequences $u_i \equiv \{x_1^i, \cdots, x_n^i\}$ and corresponding sets A_i of sequences v of length n of y's such that the A_i are disjoint and $p(A_i \mid u_i) > 1 - e$. The interpretation of this statement is that we can transmit information through any channel with arbitrarily small probability of error if (1) we transmit at a rate $H < C$, and (2) if we code our information into sequences of sufficient length $n(e, H)$.

We wish to obtain an upper bound for e as a function of n, H and the channel parameters. We start with the inequality[2]

$$e \le \frac{1}{B}(\sqrt{A} + \sqrt{\delta_1^+})^2,$$

where

$$B = 1 - \delta_2^- \quad \text{and} \quad A = 2^{-n(C-H-\epsilon_1-\epsilon_2)}.$$

Furthermore, δ_1^+ and δ_2^- are functions of n and ϵ_1 and ϵ_2, being defined as follows:

$$\delta_1^+ = \text{Prob.}\{p(u \mid v) \equiv p(x_1 \mid y_1) \cdots p(x_n \mid y_n) \le 2^{-n(H(X \mid Y)+\epsilon_1)}\}$$

and

$$\delta_2^- = \text{Prob.}\{p(u) \ge 2^{-n(H(X)-\epsilon_2)}\},$$

where all probabilities are taken as those for which $H(X) - H(X \mid Y) = C$.

Let $Z_1, \cdots, Z_n$ be a set of independent random variables, identical to $-\log p(x \mid y)$. Then we may put

$$\delta_1^+ = \text{Prob.}\left\{\frac{Z_1 + \cdots + Z_n}{n} - H(X \mid Y) \ge \epsilon_1\right\},$$

and $E(Z_1) = \cdots = E(Z_n) = H(X \mid Y)$. We can likewise express δ_2^- in similar fashion. To estimate δ_1^+ and δ_2^- we use a theorem of Feller[3] which, for our purpose, may be stated as follows.

* The results of this paper were obtained while the author was working at the Bell Telephone Laboratories, Murray Hill, N. J., for the summer of 1954. At the same time, C. E. Shannon obtained by a method distinct from ours substantially the same results, plus preliminary results concerning a lower bound for the error. It was intended at that time to publish one paper containing all these results. Since then, however, Dr. Shannon has informed the author of several important new results which he has obtained. Under these circumstances it seemed more appropriate to publish these results separately.

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[1] C. E. Shannon, "A mathematical theory of communication," *Bell Sys. Tech. Jour.*, vol. 27, pp. 379–423, 623–656; 1948.

[2] A. Feinstein, "A New Basic Theorem of Information Theory," Dept. of Physics, MIT, September, 1954; or equivalently, IRE *Trans. P.G.I.T.*, "Title," September, 1954.

[3] W. Feller, "Generalization of a Probability Limit Theorem of Cramer," *Trans. Amer. Math. Soc.*, vol. 54, pp. 361–372; 1943.

Theorem. Let $\{X_i\}$, $i = 1, \cdots, n$ be a set of independent, identically distributed, bounded random variables. Let $S = \sum_{i=1}^{n} X_i$ and let

$$F(x) = \text{Prob}\,\{S - nE(X_1) \leq x\}.$$

Put $\sigma^2 = E([X_1 - E(X_1)]^2)$ and take

$$\lambda > \frac{\sup |X_1 - E(X_1)|}{\sigma n^{1/2}}.$$

Then if $0 < \lambda x < 1/12$, we have

$$1 - F(x\sigma n^{1/2}) = \exp[-1/2x^2Q(x)][\{1 - \Phi(x)\} + \theta\lambda \exp(-1/2x^2)],$$

where

$$|\theta| < 9, \quad |Q(x)| \leq \frac{1}{7}\left(\frac{12\lambda x}{1 - 12\lambda x}\right)$$

and

$$\Phi(x) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{x} \exp[-y^2/2]\,dy.$$

In our case, $x = \frac{\epsilon_1}{\sigma} n^{1/2}$ and we may take[4]

$$\lambda = \frac{2 \sup |X_1 - E(X_1)|}{\sigma n^{1/2}}.$$

Now as $x \to \infty$, $1 - \Phi(x) \sim \frac{1}{(2\pi)^{1/2}x} e^{-x^2/2}$; hence for $x \geq a$ for suitable a, $1 - \Phi(x) \leq \frac{e^{-x^2/2}}{x}$. Now

$$\lambda x = \frac{2 \sup |X_1 - E(X_1)|\,\epsilon_1}{\sigma^2};$$

if we take ϵ_1 so small that $\lambda x < \frac{1}{12}$, we have:

$$\delta_1^+ \leq \exp\left\{\frac{n\epsilon_1^2}{\sigma^2}\left[\frac{6\lambda x}{7(1 - 12\lambda x)} - \frac{1}{2}\right]\right\} \cdot n - \frac{1}{2} \cdot \left[\frac{18 \sup |X_1 - E(X_1)|}{\sigma} + \frac{\sigma}{\epsilon_1}\right],$$

provided that $\frac{\epsilon_1}{\sigma} n^{1/2} \geq a$. Let us take $\epsilon_1 = A_1(C - H)$. If A_1 is sufficiently small,

$$\frac{6\lambda x}{7(1 - 12\lambda x)} - \frac{1}{2} \leq -\frac{1}{4},$$

say, for any $H < C$. We can now say that, given a value of H, we have $\delta_1^+ \leq e^{-B_1 n(C-H)^2}$, where $B_1 = \frac{A_1^2}{4\sigma^2}$ provided that n is so large that

$$\frac{A_1(C - H)}{4\sigma} n^{1/2} \geq a$$

and

$$n^{-1/2}\left\{\frac{18 \sup |X_1 - E(X_1)|}{\sigma} + \frac{\sigma}{A_1(C - H)}\right\} \leq 1.$$

It is, however, easy to remove these conditions, as follows. Both conditions require that the smallest value of n, for which both conditions are satisfied, is proportional to $\frac{1}{(C - H)^2}$. This implies that the value of $e^{-B_1 n(C-H)^2}$ when it becomes a true bound for δ_1^+ is some constant K_1 $0 < K_1 < 1$, independent of $C - H$. The expression

$$\frac{1}{K_1} e^{-B_1 n(C-H)^2}$$

is then certainly a bound for δ_1^+ whenever $e^{-B_1 n(C-H)^2}$ is. Further, wherever the latter fails, the former is greater than 1, and certainly greater than δ_1^+. Hence, without qualification, $\delta_1^+ \leq \frac{1}{K_1} e^{-B_1 n(C-H)^2}$.

We can similarly obtain $\delta_2^- \leq \frac{1}{K_2} e^{-B_2 n(C-H)^2}$, taking $\epsilon_2 = A_2(C - H)$ for suitably small A_2.

Now $e \leq \frac{1}{B}(\sqrt{A} + \sqrt{\delta_1^+})^2$. Since

$$A = 2^{-n(C-H-\epsilon_1-\epsilon_2)},$$

$$A = 2^{-n(1-A_1-A_2)(C-H)} \leq 2^{-n\frac{1-A_1-A_2}{c}(C-H)^2}$$

as long as we take $A_1 + A_2 \leq 1$. We therefore have $e \leq \frac{1}{B} e^{-Dn(C-H)^2}$ for suitable positive D. However, $\frac{1}{B} = \frac{1}{1 - \delta_2^-}$; to keep $\frac{1}{B}$ bounded we want δ_2^- bounded away from 1. Now $\delta_2^- \leq \frac{1}{K^2} e^{-B_2 n(C-H)^2}$. If, say, we want $\frac{1}{B} \leq 2$, or $\delta_2^- \leq \frac{1}{2}$, we must keep $n(C - H)^2$ constant. But, as before, we can eliminate this restriction by multiplying $\frac{1}{2}e^{-Dn(C-H)^2}$ by a suitable factor. We finally have $e \leq Fe^{-Dn(C-H)^2}$,[5] where F and D depend upon the channel parameters but not upon n or H.

[4] For $\lambda < \infty$ it is clearly sufficient that the channel have only a finite number of received signals, since the number of transmitted signals we always assume finite. See also the reference of footnote 2 for various remarks on this.

[5] There should be no confusion between e, the probability of error, and e, the base of the natural logarithms.

A Bibliography on Noise

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THIS BIBLIOGRAPHY is an attempt to collect a reasonably complete set of references pertaining primarily to fluctuation type noise, characteristic of shot and thermal noise, up to the year 1954. Of necessity these references touch upon such diverse fields as electrical engineering, aerodynamics, quantum mechanics, mathematical statistics, and pure mathematics. Although the material has been divided into a number of broad categories, it should be pointed out that many references could appear with almost equal validity under more than one heading. The classification is somewhat arbitrary and the reader is advised to consider related topics in all cases. Within each category the items are arranged chronologically with respect to their appearance in print. The attempt has been made to survey as accurately as possible the field in English, and to include as many pertinent and accessible foreign-language articles as practicable.

Because noise is the relentless and undesirable associate of intelligence transmitted or received by acoustical and electronic systems, it is essential for any proper theory of communication to provide suitable knowledge and methods for studying the physical properties of noise and its interaction with a desired signal. Not only is a successful technique of measurement required to control or lessen the noise, but also adequate information and theory is requisite to guide experiments and to interpret data. The purpose, therefore, of this bibliography is to present a coherent source of information references for the case of noise belonging primarily to the fluctuation type (random normal processes), rather than impulsive noise such as atmospheric and solar static, the cataloguing of which would have been prohibitive due to the enormous number of publications of observations.

Classification Chart

1. Source Works: basic texts, monographs, and auxiliary bibliographies.
2. Internal Noise Sources: tube noise, circuit element noise, etc.
3. External Noise: signals received in the presence of noise, control systems with statistical inputs.
4. Noise Generation and Measurements.
5. Impulsive Type Noise: atmospheric and solar noise.
6. Modulation and Noise: noise and PM, PCM, PTM, AM, and FM systems.
7. Radar Applications: jitter, clutter, glint, scintillation, etc.
8. Noise, Communication and Filtering: data smoothing, Wiener theory, etc.
9. Statistical Theory: general studies of random noise, generalized harmonic analysis, etc.
10. Author Index: alphabetical listing.
11. Appendix: publisher listing.

In past years, since Schottky*[2-1] first noted and correctly interpreted shot effect, the subject of fluctuation noise was quite mysterious even to the best of engineers and scientists. In 1928, however, Johnson[2-3] and Nyquist[2-4] cleared up the subject of thermal agitation noise in circuits. From about 1935, fluctuation noise in the plate circuit of amplifier tubes has been thoroughly worked out[2-15], and, with some further work on mixer noise and converter noise[3-4,3-7], it is possible to use accurate qualitative data on tube noise for receiver calculations. At high frequencies, however, input noise must be considered; this too has been evaluated[2-20,2-19]. The signal-to-noise ratio of a radio receiver at ultra-high frequencies is primarily dependent on noise relations for tubes and circuits[2-29], but also one must consider the input signal and its transmission to and through the receiver. Early published works[4-3,2-12] on signal-to-noise ratio did not include induced input noise and hence was not strictly applicable at uhf. Until North's paper[3-8] on the quantity called "noise factor", there was no widely accepted basis on which to compare qualitatively experimental or analytical results. The extension of the analysis to include induced noise was made[3-7], and the interpretation of results in terms of noise factor has become common. As a result it was possible to discuss signal-to-noise ratio at uhf with considerable clarity[2-29,2-38].

Since the paper by Armstrong[6-1] drew attention to the possibilities of frequency modulating regarding the reduction of noise, a considerable quantity of work in this direction has been published. The earlier theoretical treatment of signal and noise, however, had been confined in the main to the case where the noise energy is small as compared to the signal energy. Now rigorous treatments valid for all signal-to-noise energy ratios may be found. These treatments are usually developed by methods which Rice[9-12] and Fränz[4-8, 4-10] applied to similar problems and which are based on the Fourier Spectrum of the noise[1-1, 1-5, 1-8, 1-12, 9-2, 9-9, 9-17].

In the past fifteen years a great deal of study has been aimed at the mathematical analysis of random noise in communication systems[9-46]. Theoretical contributions have been made by many people, among whom are Rice,

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* *Editorial note*—All superscripts refer to bibliographical data which follows, in this manner: In superscript [2-1], e.g., "2" designates section 2 (Internal Noise Sources), and "-1" refers to the first author listed, etc.

mentioned earlier,[9-27] and Middleton[3-19, 3-25, 3-32, 3-46, 3-58, 7-12, 9-59]. The former's papers give a unified view of the fundamental methods of noise analysis for both linear and nonlinear circuits. The latter has solved a good number of nonlinear problems of practical importance.

Since the mathematics is quite complicated[9-67, 9-68], a need for developing experimental techniques to determine the important statistical characteristics of random noise in circuits, and, incidentally, to check existing theoretical results and to solve problems not susceptible to theoretical analysis was felt in many quarters. The method usually consists of finding the autocorrelation function[9-85] and by a Fourier cosine transformation determining the power density spectrum[9-72, 9-74]. At MIT's Research Laboratory of Electronics, for example, there are available an electronic digital correlator[9-41] and other devices, such as the electronic differential analyzer[9-28] and the delay line filter[8-37]. The last two machines accomplish the transformation of the correlation experimentally obtained by the first. Some work by Knudtzon[8-26] was done in this direction where, however, experimental studies were limited to the case of linear circuits. On the other hand, Weinberg and Kraft[9-86] have extended the scope of investigation via the correlation technique to include nonlinear devices.

The determination of an optimum design for an automatically tracking radar-controlled system is hampered by the difficult problem of analyzing the character of the radar noise. The engineer who wishes to minimize the effect of the noise in the tracking loop, for example, may use the Wiener "Optimum Synthesis" technique[9-6] to determine the characteristics of an optimum linear control system. The equations which are based on the criterion of minimizing the rms error on a statistical basis are discussed in[1-6]. The synthesis of such a system requires the aforementioned autocorrelation function and power-density spectra of the input message and noise characteristics, in order that the power spectra may be placed into the design equations to obtain the optimum system. Phillips and Weiss[3-16] concerned themselves with the best smoothing of positional data for gunnery prediction for noise spectra of arbitrary forms, while Floyd, Zadeh, and others[8-22, 8-32, 8-39] extended Wiener's theory[1-9] to nonstationary time series, and obtained a more general solution to this problem.

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upplement to

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Note on Abstracts

(381, 1955) at the end of a line refers to abstract 381 of the abstracts and references section of Proc. IRE (1955).

(A 10726, 1953) refers to abstract 10726 of *Physics* Abstracts 1953.

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Correspondence

Proceedings or Transactions?

Questions frequently arise—in Editorial Board discussions and among the reviewers of PROCEEDINGS papers—as to what should be published in the PROCEEDINGS OF THE IRE and what should be published in the various TRANSACTIONS. This statement will not settle the matter, but it does clarify the present situation and speculate about future possibilities.

One aspect of the current state of affairs is that of the twenty-three Professional Groups of the IRE, twenty-one publish TRANSACTIONS, while only ten of the twenty-one TRANSACTIONS appear regularly. Thus, in some fields of interest the PROCEEDINGS is the IRE's only facility for publication, and in some it is the only regularly published facility. As long as this situation persists, there must be a certain seeming inconsistency in the publication policies of the PROCEEDINGS. In some fields the PROCEEDINGS will endeavor to publish all papers worthy of publication, and in other fields it will publish only a selected few of these papers. It is to be hoped, of course, that neither TRANSACTIONS nor PROCEEDINGS will publish papers which are not worthy of publication.

We hope that this inequity of coverage by the PROCEEDINGS is a temporary matter. While it continues, the PROCEEDINGS will have to cover some fields in more detail than is perhaps desirable and it may publish too little in the fields of the most active and effective Professional Groups. The remedy for this situation is obviously a continued expansion and improvement in the TRANSACTIONS, and effective liaison between editors of TRANSACTIONS and PROCEEDINGS.

Let us now consider the specific case in which a field is covered both by an active Professional Group with a fine TRANSACTIONS which appears regularly, and by the PROCEEDINGS. Among all papers worthy of publication, which should go to the PROCEEDINGS and which should go to the TRANSACTIONS? Above all, whatever the decision should be, papers should get into the right journal as promptly as possible. While an initial mistake might in some measure be remedied by republishing in the PROCEEDINGS a paper which appeared first in the TRANSACTIONS, this is bad, and papers will be reprinted only under the most unusual circumstances. A technical journal is most valuable and most interesting to its readers when its contents are fresh and new. What about simultaneous publication in the PROCEEDINGS and in the TRANSACTIONS? This is pointless, for the PROCEEDINGS reaches all members of the IRE. The problem, then, is to get the papers into the right journal the first time, and promptly.

It is not easy to lay down rules which will cover all papers. There is certainly a place in the PROCEEDINGS for review papers which summarize recent progress in a field, and for tutorial papers which teach new concepts and techniques of analysis. The PROCEEDINGS asks experts to write such papers.

Most of the material in the PROCEEDINGS is submitted unsolicited. In trying to lay down rules for reviewing papers, the Editorial Board has said that to appear in the PROCEEDINGS papers should be important enough to be of general interest (to a reasonable fraction of the Institute's 40,000 members). This has been further interpreted by saying that papers should represent either a contribution of permanent value, or sound work of great current interest.

In being more specific than this, one can only describe and comment on particular types of papers.

A paper submitted to the TRANSACTIONS or the PROCEEDINGS may constitute a sort of review or tutorial paper if it presents a rational approach to a new field quite clearly or completely, so that one unfamiliar or only slightly familiar with the field can use it. Such a paper may or may not contain important new information. If it is really good, it will be suitable for the PROCEEDINGS.

A paper may describe an important new invention or device. If this device has considerable present or potential importance, and if it has real novelty, the membership of the IRE should know about it promptly in a paper of length adequate to explain it clearly. Perhaps the author will want to treat at length many important details which are of interest largely to specialists; he should do so in the TRANSACTIONS. The PROCEEDINGS paper should, however, be a real technical paper and not a news item; it should be technically sound and complete enough so that a more detailed discussion can be based on it and can refer to it.

A new experimental result, or new theory, should be treated much as is a new invention or device.

Many papers are concerned with calculations of great importance, about, for example, vacuum tubes, networks, antennas, or solid-state devices. If a calculation exhibits a new and important principle which casts new light on important problems, it is suitable for the PROCEEDINGS. If it merely solves a particular difficult problem by ingenious but special methods, it will usually be of interest only to specialists. In such a case, the result, if it is important, can be conveyed to the general IRE membership through the abstracts of TRANSACTIONS papers which appear in the PROCEEDINGS, or through a letter to appear as Correspondence.

In all cases, we should ask, "Should people outside a particular Professional Group be told about the contents of the paper? Why should they be told? How much should they be told to make the telling a real technical communication and not a news note?"

Where should an author send his paper? If he believes that he has something to say to the entire IRE membership, he should send it directly to the PROCEEDINGS. If he is addressing only experts in his field, he should send it to the TRANSACTIONS. To assure the promptest publication the author should make the right choice.

Sometimes the author makes the wrong choice. It is up to the reviewers to be alert about this, and to recommend to the PROCEEDINGS or TRANSACTIONS a paper which they feel has been misdirected. This makes some sort of liaison desirable. Several Professional Groups have named one or more of their members to act as one of the three PROCEEDINGS reviewers on all papers in the field of their Group. This makes available at the time of the review for the PROCEEDINGS the opinion of a representative of the Professional Group.

The relationship between the TRANSACTIONS and the PROCEEDINGS must evolve. During this evolution, it is important that at each stage both the TRANSACTIONS and PROCEEDINGS publish promptly interesting and worthwhile material. The material must be worthwhile in each case, and perhaps the chief distinction must be between what is interesting to a large and heterogeneous group and with what is interesting to a specialized segment.

J. R. PIERCE
Editor, IRE

A Note on the Bounds on Autocorrelation Functions

As is well known, the autocorrelation function $\psi(\tau)$ attains its maximum value at τ equal to zero. Furthermore, if the autocorrelation function vanishes for $|\tau| \geq T$, then for $|\tau| < T$:

$$| \psi(\tau) | \leq \psi(0) \cos \frac{\pi}{\left[\frac{T}{\tau}\right] + 1}, \qquad (1)$$

where $[T/\tau]$ is the least integer not less than $T/|\tau|$.[1]

Recently, bounds were shown to exist on the transient response of networks whose system functions were appropriately restricted.[2,3] Since the impulse response and real part of the system function are Fourier cosine transforms of each other and the autocorrelation function and power spectrum for stationary processes are similarly related by (2) and (3), many of

$$w(f) = 4 \int_0^\infty \psi(\tau) \cos 2\pi f\tau \, d\tau, \qquad f \geq 0 \qquad (2)$$

[1] R. P. Boas, Jr., and M. Kac, "Inequalities for Fourier transforms of positive functions," *Duke Mathematical Journal*, vol. 12, pp. 189–206; March, 1945.

[2] A. H. Zemanian, "Bounds existing on the time and frequency response of various types of networks," PROC. IRE, vol. 42, pp. 835–839; May, 1945.

[3] A. H. Zemanian, "Further bounds existing on the transient responses of various types of networks," PROC. IRE, vol. 43, pp. 322–326; March, 1955.

$$\tau) = \int_0^\infty w(f) \cos 2\pi f \tau \, df \qquad (3)$$

ese results may be applied directly to the tocorrelation. This analogy depends on e fact that the power spectrum is a non-gative function. The results will be stated thout proof, since these proofs appear ewhere. It is merely a matter of substi-ting the appropriate variables for those pearing previously in the papers on tran-nt response. That is, one-fourth of the wer spectrum $[w(f)]/4$ is analogous to the al part of the system function $R(\omega)$ and e autocorrelation function $\psi(\tau)$ is analo-us to the impulse response $W(t)$. Thus τ places t, $\psi(0)$ replaces $1/C$, and $[w(0)]/4$ places r in the previous papers. $\psi(0)$ is the tal power of the signal.

The first result is obtained from Theorem of reference 2, and is similar to the bound tained by Boas given by (1) above. In is case, the condition that the autocorrela-n function vanishes for all $|\tau| \geq T$ is placed by the less restrictive condition at the autocorrelation function be bound-by some fraction of its maximum value. sulting bounds for $|\tau| < T$ are, however, t so strong as those obtained by Boas.

Theorem: If $\psi(\tau) \leq \epsilon\psi(0)$ for $|\tau| \geq T$ where $0 \leq \epsilon \leq 1$,

$$\text{then for } \frac{T}{2} \leq |\tau| < T: \quad |\psi(\tau)| < (0.637 + 0.638\epsilon)\psi(0);$$

$$\text{for } \frac{T}{3} \leq |\tau| < \frac{T}{2}: \quad |\psi(\tau)| < (0.785 + 1.916\epsilon)\psi(0);$$

$$\text{for } \frac{T}{4} \leq |\tau| < \frac{T}{3}: \quad |\psi(\tau)| < (0.907 + 0.493\epsilon)\psi(0);$$

$$\text{and for } 0 \leq |\tau| < \frac{T}{4}: \quad |\psi(\tau)| \leq \left[1 - \frac{\tau^2}{4T^2}(1-\epsilon)\right]\psi(0).$$

The second result is obtained from Theo-m II of reference 3. It is applicable if the wer spectrum is monotonic decreasing for reasing positive frequencies.

Theorem: If $\frac{dw}{df} \leq 0$ for $f \geq 0$, then

$$|\psi(\tau)| \leq \psi(0) \frac{\sin\left[2\pi\tau \frac{\psi(0)}{w(0)}\right]}{2\pi\tau \frac{\psi(0)}{w(0)}} \quad \text{for} \quad |\tau| \leq \frac{w(0)}{4\psi(0)}$$

$$|\psi(\tau)| \leq \frac{w(0)}{2\pi\tau} \quad \text{for} \quad |\tau| \geq \frac{w(0)}{4\psi(0)}.$$

can be shown that the upper bound is west possible for all τ and that the lower und is highest possible for $\tau \geq \frac{3\psi(0)}{4w(0)}$.

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Some Thoughts on Technical Meetings

As a result of my recent experiences as Chairman of the Organizing Committee of the 1954 Symposium on Information Theory, I have given some thought to the general problem of technical meetings with particular regard to the relative functions of Professional Group symposia and the technical sessions at the National Convention. I am jotting down my thoughts on this matter, as I understand that the organization of technical meetings is a subject of current interest to many IRE members.

I shall begin with a brief report on the 1954 Symposium on Information Theory. The organization of the Symposium departed from current practice in two major respects. In the first place, all papers presented at the Symposium were published in a special issue of the Transactions of the Professional Group on Information Theory and distributed to all participants two weeks before the date of the Symposium. In the second place, ample time was allotted to discussion; it averaged about one-half hour per paper, while the formal presentation of the papers averaged about 20 minutes. Furthermore, a Discussion Leader was formally appointed ahead of time for each of the Symposium's 6 sessions; function of the Discussion Leader was to start discussion off on the right track by making carefully prepared comments about each paper.

* Received, October 13, 1954; revision received, July 9, 1955.

The total number of registrants was 300. Although I did not make detailed checks, I would say the attendance at all sessions averaged between 80–90 per cent of registration. The discussion was quite lively most of the time and had to be stopped by the Chairman to keep the meeting on schedule. I noticed with particular pleasure that most of the Discussion Leaders, Chairmen, and Authors attended all 6 sessions and seemed to enjoy the meeting. All in all, the consensus seemed to be that the unconventional features of the Symposium represented a step in the right direction. It was obvious, however, that a technical meeting such as that could not be attended by any appreciably larger audience.

The 1954 Symposium on Information Theory met fairly well, in my opinion, the needs of the relatively small group of IRE members who are doing active research in the field of information theory. I felt that the discussion was fruitful in stressing the present state of development and in suggesting avenues of approach to unsolved problems. On the other hand, I doubt that a person interested primarily in specific practical applications or one interested in keeping up-to-date in general terms with the over-all progress in information theory, could have learned much by attending the Symposium. The realization of this fact brought to my mind the problem of how to meet the different technical needs represented in the IRE membership.

Broadly speaking, I would say that the IRE members interested in each specialized field represented by a particular Professional Group may be divided into three main groups:

A. Members who are doing active advanced research in the field and who, therefore, badly need opportunities for thorough discussion among themselves;
B. Members who are interested in specific practical developments and who, therefore, need to keep abreast of results obtained by the people in group A, as well as by people doing similar developmental work; and
C. Members who, for various reasons, wish to keep themselves informed of the broad lines of progress in the field, but are not interested in the detailed developments.

Two points should be noted in this regard. First of all, the size of group A is relatively small in each specialized field, while groups B and C are rather large. In the second place, a person who fits in group A for one particular field will in general fit into group B or C in other fields. In other words, the three groups represent divisions of *interests* and not divisions of *people*, so that the same IRE members may be grouped in different ways for different fields.

My feeling is that for groups A and C live technical meetings are at least as necessary and as effective as printed articles. However, while technical meetings for group A should emphasize advanced research and allow ample time for discussion, the meetings for group C should consist primarily of up-to-date review and tutorial papers presented by appropriate experts. Professional

Group symposia are eminently suited to meet the needs of group A. In this respect I believe that the organization of the 1954 Symposium on Information Theory was a step in the right direction and that the effectiveness of future similar meetings will increase, once the audience becomes accustomed to carefully reading the printed papers ahead of time. On the other hand, the sessions at the National Convention should be devoted primarily to meet the needs of group C through the presentation of review and tutorial papers, and of original papers of broad significance. This suggestion appears to be in line with the present editorial policy of devoting the PROCEEDINGS OF THE IRE to contributions of interest to a broad audience and to invited tutorial papers. Some of the review papers could well be reports on the latest developments that have emerged at Professional Group Symposia or other important technical meetings. It should be noted in this connection that the National Convention is just the occasion in which IRE members have the opportunity of keeping themselves informed about a number of fields without any undue expenditure of time. Personally, I feel that in addition to the pleasure of meeting old friends, it is a broad up-to-date education that I would like to obtain from the National Convention.

The needs of groups A and C can thus be met without much difficulty. On the other hand, the organization of technical meetings designed to meet the special needs of group B presents serious problems. Any meeting dealing with developmental work is bound to be attended by such a large number of people that worthwhile discussion from the audience is precluded for all practical purposes. Even the formal presentation of original technical papers constitutes a very serious problem, because very often the importance of developmental papers resides in details, the significance of which can hardly be conveyed in a short time to an audience unfamiliar with the background of the specific problem. Perhaps review papers covering systematically recent work in each problem of interest are still a reasonably good answer to the needs of group B. In any case, it seems to me that the needs of group B can be met more realistically by the quick distribution of printed literature than by live technical meetings.

The fact of the matter seems to be that the needs of groups A and C are still fairly similar to those felt back in the past by members of learned societies, and therefore can still be fulfilled by meetings and publications of the traditional form. The existence of very large groups of the B type, on the contrary, is a new phenomenon resulting from the tremendous expansion of the electronics industry in the last decade. The needs of these groups present new problems on which little experience is yet available, and which are often made more difficult by failure to recognize their nature.

The problem of how the Institute can best keep serving the technical needs of its fast growing membership deserves careful thought on the part of all concerned. Perhaps the classification of interests used above is not quite appropriate. Yet, I feel that full recognition must be given to the wide range of interests—research, development, management, etc.—required in the modern electronic industry, and to the obligation of serving all such interests with equal professional and intellectual standards, within the framework of the Institute of Radio Engineers.

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PGIT News

REPORT ON INFORMATION THEORY AND MODULATION SYSTEMS COMMITTEE

The Information Theory and Modulation Systems Committee, under the Chairmanship of J. C. Kreer, Jr., is now working on the very difficult problem of definitions in the field of information theory. Among the definitions now being considered are:

Bit: A unit of information content or capacity, equal to the information content in a binary decision between equally probable states.

Channel: A transmission path and associated terminal equipment capable of receiving signals at one point and delivering related signals at another point.

Code: A set of transformation rules to be applied to messages or signals.

Code Character: The signal representation of a discrete value or symbol in a message.

Code Element: One of a finite set of parts from which code characters may be constructed.

Hartly: A unit of information content or capacity, equal to the information content in a decimal decision between ten equally probable states.

Information Content (of a message from a source): The negative logarithm of the probability that that particular message will be emitted by the source.

Signal: The physical embodiment of a message.

The Committee is anxious to receive any comments, variations, or definitions that IRE members may have as soon as possible. Comments sent to the Professional Group on Information Theory will be forwarded to the Committee.

INFORMATION FOR AUTHORS

Authors are requested to submit editorial correspondence or technical manuscripts to the Publications Chairman for possible publication in the PGIT TRANSACTIONS. Papers submitted should include a statement as to whether the material has been copyrighted, previously published, or accepted for publication elsewhere.

Papers should be written concisely, keeping to a minimum all introductory and historical material. It is seldom necessary to reproduce in their entirety previously published derivations, where a statement of results, with adequate references, will suffice.

To expedite reviewing procedures, it is requested that authors submit the original and two legible copies of all written and illustrative material. The manuscript should be double-spaced, and the illustrations drawn in india ink on drawing paper or drafting cloth. Each paper should include a carefully written abstract of not more than 200 words. Upon acceptance, papers should be prepared for publication in a manner similar to those intended for the PROCEEDINGS OF THE IRE. Further instructions may be obtained from the Publications Chairman. Material not accepted for publication will be returned.

IRE TRANSACTIONS ON INFORMATION THEORY is published three times a year, in March, September, and December. A minimum of one month must be allowed for review and correction of all accepted manuscripts. A period of approximately two months additional is required for the mechanical phases of publication and printing. Therefore, all manuscripts must be submitted three months prior to the respective publication dates. There will be no June issue, since the IRE CONVENTION RECORD is published at that time, and a bound collection of Information Theory papers previously delivered at the 1955 Convention will be mailed gratis to all PGIT members.

All technical manuscripts and editorial correspondence should be addressed to Laurin G. Fischer, Federal Telecommunications Labs., 492 River Road, Nutley, N. J. Local Chapter activities and announcements, as well as other nontechnical news items, should be addressed to Nathan Marchand, Marchand Electronic Labs., 255 Mill Street, Byram, Conn.